INFLUENCE OF FIBER AND MATRIX VARIABLES ON THE FATIGUE AND CREEP CHARACTERISTICS OF HYBRID COMPOSITES

Final Report

(April 1, 1976 to July 31, 1976)

November 1977

by

K. E. Hofer, Jr.
L. C. Bennett

IIT Research Institute

for

Department of the Navy
Naval Air Systems Command
Washington, D.C. 20360

CODE AIR-52032D

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-- 1 OF 3
-- ***DTIC DOES NOT HAVE THIS ITEM***
-- 1 - AD NUMBER: D429137
-- 5 - CORPORATE AUTHOR: IIT RESEARCH INST CHICAGO IL
-- 6 - UNCLASSIFIED TITLE: INFLUENCE OF FIBER AND MATRIX VARIABLES ON
-- THE FATIGUE AND CREEP CHARACTERISTICS OF HYBRID COMPOSITES.
-- 9 - DESCRIPTIVE NOTE: FINAL REPT.,
--10 - PERSONAL AUTHORS: HOFER,K. E. , JR.;BENNETT ,L. C. ;
--11 - REPORT DATE: NOV , 1977
--12 - PAGINATION: 93P
--14 - REPORT NUMBER: D6120
--15 - CONTRACT NUMBER: N00019-75-C-0470
--20 - REPORT CLASSIFICATION: UNCLASSIFIED
--22 - LIMITATIONS (ALPHA): APPROVED FOR PUBLIC RELEASE; DISTRIBUTION
-- UNLIMITED. ~~AVAILABILITY: NAVAL AIR SYSTEMS COMMAND, WASHINGTON, D.~~
-- ~~C. 20360~~
--33 - LIMITATION CODES: 1 [redacted]
--xxxxxx
-- 2 OF 3

IIT Research Institute
Technology Center
Chicago, Illinois 60616

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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)
Influence of Fiber and Matrix Variables on the Fatigue and Creep Characteristics of Hybrid Composites

5. TYPE OF REPORT & PERIOD COVERED
Final Technical Report

6. PERFORMING ORG. REPORT NUMBER
D6120

7. AUTHOR(s)
K.E. Hofer, Jr. and L.C. Bennett

8. CONTRACT OR GRANT NUMBER(s)
N00019-75-C-0470

9. PERFORMING ORGANIZATION NAME AND ADDRESS
IIT Research Institute
10 W. 35th Street
Chicago, Illinois 60616

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS

11. CONTROLLING OFFICE NAME AND ADDRESS
Naval Air Systems Command
Washington, D.C. 20360

12. REPORT DATE
November, 1977

13. NUMBER OF PAGES
93

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)
N.A.

15. SECURITY CLASS. (of this report)
Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)
Approved For Public Release, Distribution Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)
N.A.

18. SUPPLEMENTARY NOTES
N.A.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)
~~Advanced Composites~~, Hybrid ~~Composites~~, ~~Fiber-Reinforced Plastics~~, ~~Graphite Fibers~~, ~~Glass Fibers~~, Fatigue, Creep, Environmental Conditioning, ~~Thornel 300~~ Graphite T300 Laminates, Moisture Weight Gain. Fiberglass S Epoxy 5208 Stacking Effects ~~Sequence~~

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The study described herein was conducted to establish the effect of simultaneously applying a hostile (high humidity) environment and fatigue stress cycling on the mechanical response of glass/graphite/epoxy hybrid composites. The effect of prolonged tensile loading on the strength of these hybrids was also investigated.

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Comparison between the results of this program and a similar prior program were made in an effort to correlate the effect of stacking sequence on the fatigue resistance of hybrid composites.

The results indicate that the tensile fatigue resistance of hybrid composites increase over unexposed composites. The elastic moduli of the hybrids investigated remained constant over the range of 10^3 to $2x10^6$ cycles. The residual strength reduced with cycling and a substantial and definable increase in Poisson's ratio with stress cycling was noted.

FOREWORD

This technical report was prepared by the Mechanics of Materials Research Division of the IIT Research Institute, Chicago, Illinois. The authors include K. E. Hofer, Jr. responsible for overall program management and acting as the principal investigator, L. C. Bennett, responsible for the fatigue testing aspects of this effort. Other supporting staff for this effort include Renard Porte, creep testing engineer and T. Todner, composite fabrication.

The effort described was conducted in support of materials studies for the Naval Air Systems Command during the period April 1, 1976 through July 31, 1977. M. Stander (AIR 52032D) was the program monitor on behalf of the Naval Air Systems Command.

This report was submitted by the authors November, 1977.

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SECTION I

1.0 INTRODUCTION

The objective of this program was to establish the interaction of high-humidity, stacking sequence and fatigue stresses on the mechanical behavior and creep characteristics of hybrid graphite/glass/epoxy composites suitable for application to the stringent requirements of Naval Aircraft.

The fatigue test program is shown in Table I. It shows the various environmental preconditioning treatments which are purportedly degradative to advanced fiber/epoxy composites. Table II presents the creep test program which was aimed at establishing the long term resistance of graphite/glass/epoxy hybrid composites to sustained mechanical loads.

TABLE I

TENSILE FATIGUE TESTING PROGRAM FOR VARIOUS HUMIDITY PRECONDITIONING TREATMENTS WITH STACKING VARIATIONS OF THE HYBRID COMPOSITES

MATERIAL	PRECONDITIONING TREATMENT	0°		QUASI-ISOTROPIC	
		SN	RESID. σ	SN	RESID. σ
Hybrid 1:1*	Baseline	15	5	10	-
	300 hrs/98% RH/165°F	5	5	5	5
Hybrids 2:1*	Baseline	15	5	10	-
	300 hrs/98% RH/165°F	5	5	5	5
Hybrids 1:2*	Baseline	15	-	10	-
	300 hrs/98% RH/165°F	5	5	5	5

* Ratio of Graphite to Glass

TABLE II CREEP AND STRESS RUPTURE PROGRAM FOR GRAPHITE/GLASS HYBRID COMPOSITES DRY AT 70°F

ORIENTATIONS

Hybrid Type	0°	Quasi-Isotropic
	RT	RT
1:1	5	5
	5	5
1:2	5	5
2:1	5	5

SECTION II

2.0 MATERIALS AND FABRICATION

It was important in this program to utilize materials which would form the basis of comparison for the results of this current study. Hofer (1)* utilized a material of current interest T-300/Narmco 5208 prepreg and it was decided to use this material for the studies described herein.

The complete ternary system was T-300 Graphite/S-Glass rovings/Narmco 5208. In an earlier study by Rao and Hofer[2] the importance of properly interleaving the layers of glass prepreg and graphite prepreg was demonstrated and this process was followed in this study as well as that of reference 1. Although it had been shown that the cost effectiveness of glass is best realized when the stiffer graphite prepreg layers are utilized as the surface plies there were indications that glass outer layers would afford some protection for the inner graphite plies and hence one of the purposes here was to investigate the effect of alternative stacking sequences on fatigue and creep life. This had the unfortunate side effect that some of the composites were constructed in the core-shell manner with increased shear stresses at the glass to graphite transitions between plies.

Table III shows the ply stacking sequences used for the basic and hybrid composites used in the fatigue and creep studies (see Tables I and II) and the ply stacking sequences previously studied in reference 1.

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* Numbers in parenthesis refer to the references section at the end of this report.

TABLE III

MATERIAL AND STACKING ARRANGEMENTS FOR THE BASE AND HYBRID COMPOSITES MATERIALS USED IN THE FATIGUE AND CREEP TEST PROGRAMS

Plate Type	Graphite/Glass Ratio	Ply by Ply No.	Orientation For Hybrid Composites R=Graphite; L=Glass
0°	1:1	8	[OL/OR/OL/OR/OR/OL/OR/OL]
	2:1	6	[OL/OR/OR/OR/OR/OL]
	1:2	6	[OL/OL/OR/OR/OL/OL]
Q.I*	1:1	8	[± 45 L/OR/90R/90R/OR/∓ 45L]
	2:1	12	[± 45 L/OR/90R/90R/OR/OR/90R/90R/ OR/∓ 45 L]
	1:2	12	[± 45 L/OR/90R/90L/OL/OL/90L/90R/ OR/∓ 45 L]
0°	0:1***	6	[0/0/0/0/0/0]
	1:0**	6	[0/0/0/0/0/0]
	1:1***	8	[OR/OL/OR/OL/OL/OR/OL/OR]
	2:1***	6	[OR/OL/OR/OR/OL/OR]
	3:1***	8	[OR/OL/OR/OR/OR/OR/OL/OR]
90°	0:1***	8	[90/90/90/90/90/90/90/90]
	1:0**	8	[90/90/90/90/90/90/90/90]
	1;1***	8	[90R/90L/90R/90L/90L/90R/90L/90R]
	2:1***	9	[90R/90L/90R/90R/90L/90R/90R/90L/90R]
	3:1***	8	[90R/90L/90R/90R/90R/90R/90L/90R]
Q.I.*	0:1***	8	[0/45/135/90/90/135/45/0]
	1:0***	8	[0/45/135/90/90/135/45/0]
	1:1***	8	[OR/45L/135L/90R/90R/135L/45L/OR]
	2:1***	12	[OR/90R/45L/135L/90R/OR/ R/90R/135L/45L/ 90R/OR]
	3:1***	16	[OR/90R/OR/90R/45L/135L/90R/OR/ OR/90R/135L/45L/90R/OR/90R/OR]

* Quasi Isotropic, ** Data Already Available
** Fatigue Data Available, ref. 3
*** Fatigue Data Available, ref. 1

The 1:1 quasi-isotropic hybrid is of the core-shell type with four ± 45° glass plies and two transitional zones of glass to graphite or vice versa. The ratio of 0° graphite to 90° graphite is 1:1. Previous studies had the same ratio of graphite to glass with four transitional zones thus being of the true interleaving type.

The 2:1 quasi-isotropic hybrid also contains four ± 45° glass plies, has two transition zones and a ratio of 0° graphite to 90° graphite of 1:1.

The 1:2 quasi-isotropic hybrid has the 1:1 ratio of 0° graphite to 90° graphite, four ± 45° glass plies, four transition zones. The ratio of 0° glass to ± 45° glass is 0.5:1.

Complete details of the fabrication process are described in Appendix I to this report.

SECTION III

3.0 ENVIRONMENTAL EXPOSURE

The most important single variable in the Naval environment has been shown to be the presence of moisture. Moisture degrades most of the epoxy resins useful for composite laminates at elevated temperatures as has been repeatedly demonstrated in the literature (1, 4, 5, 6, 7, 8, 9).

These degradatory mechanisms have serious implications wherever advanced composites either single fiber types or hybrids are employed. For this reason the effects of both long term moisture exposure and of the degradation that takes place when the humidity is coupled with temperature becomes important.

This program employed steady-state exposure to 98% relative humidity and 165°F temperature for 300 hours to simulate typical moisture absorbtion levels commensurate with saturation at high humidity locale for aircraft. No attempt was made to define a precise moisture level based on this specific composite material at a specific locale. However the exposure used is simular to that producing saturation levels in AS3501-5 after 20 years, the last year, of which, is spent in Guam (a high humidity locale).

The specimens which were subjected to humidity exposure were prepared as follows:

1) All specimens were finish machined and the tabs were bonded prior to initiation of the preconditioning treatment. For room temperature tests subject to prior humidity conditioning the adhesive was FM 1000.

2) The samples were then coated with Navy specification epoxy primer and polyurethane topcoat on the sides and all edges as well as the tabs of the specimens. The materials used were identified as primer: Epoxy, Polyamide. Topcoat: Polyurethane, Component(1) 8010-00-181-8150 base, Component(2) 8010-00-181-8150 hardener.

3) The samples were individually weighed prior to insertion in the chamber.

4) Each sample was arranged in stainless-steel holding trays in the chamber to permit maximum exposure to the moisture-laden air as it rose from the heated basin below the samples.

These steps were followed to permit rapid testing of the samples after removal from the chamber. Upon removal from the chamber, the specimens were reweighed and the moisture weight gains were noted. The tests generally could not be performed immediately due to machine unavailability, and therefore the samples were sealed in a protective vinyl, moisture proof container and restored in the chamber. These samples were then reweighed, prior to testing, to determine if moisture loss had occurred. Generally no moisture was lost in this way.

The steady state exposure of the T-300 Graphite/S-Glass/ Narmco 5208 Hybrid resulted in moisture pickup by the exposed coated samples. Figure 1 shows the moisture pickup versus time for a similar material*.

* AS3501-5A

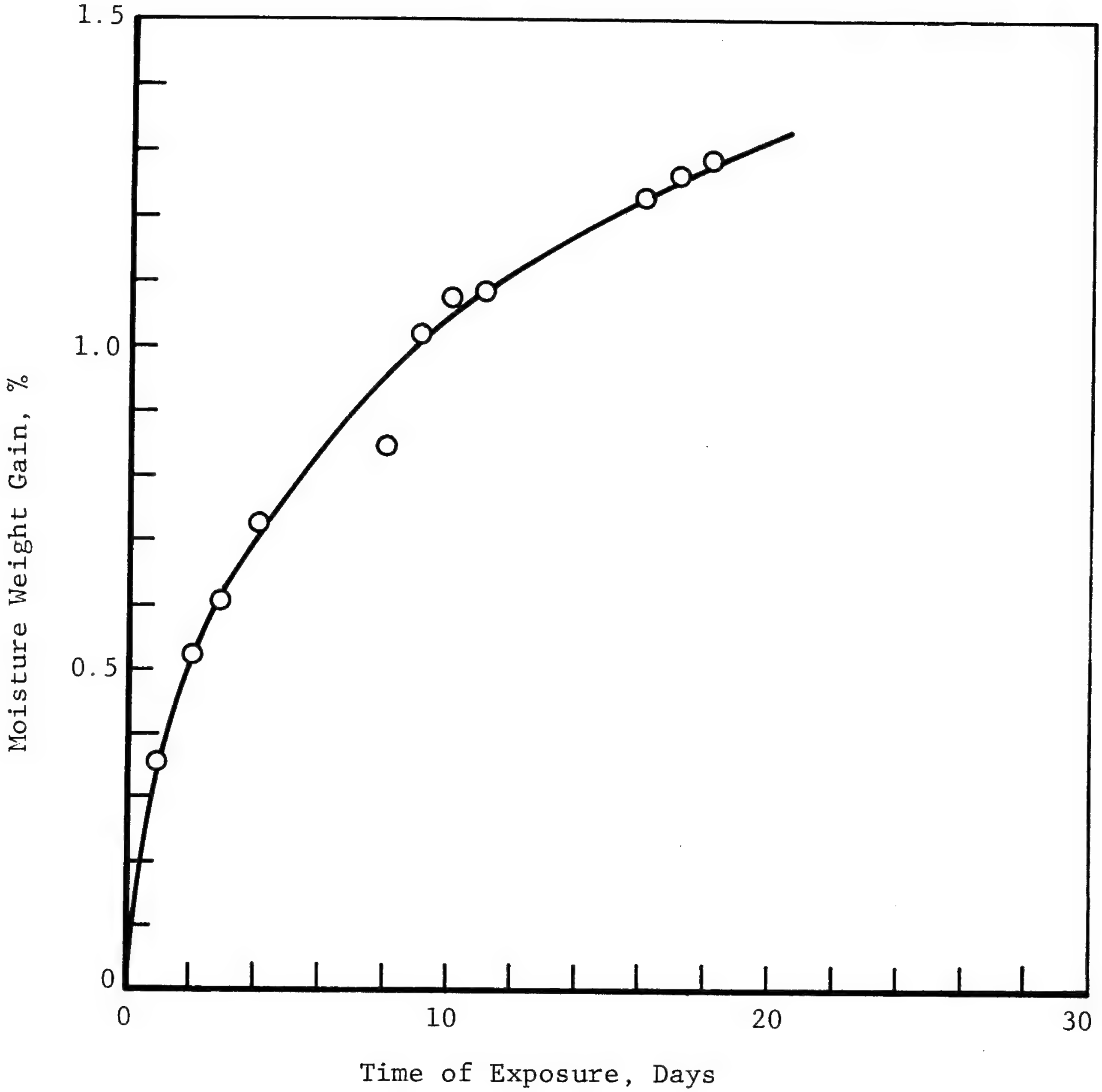


Figure 1. MOSITURE ABSORBTION OF GRAPHITE/EPOXY COMPOSITE DURING EXPOSURE TO 165°F/98% RH (AS3501-5A)

4.0 FATIGUE BEHAVIOR OF HYBRID COMPOSITES

The fatigue testing program described in Table I was performed using an SF-1-U Sonntag Universal Fatigue Testing Machine. The frequency of cycling was 30 Hertz (1800 cpm). All materials were tested in a Tension-Tension load cycle ($R = 0.1$) where

$$R = \frac{\text{Minimum Stress per Cycle}}{\text{Maximum Stress per Cycle}}$$

All specimens were bagged using a polyethylene bag throughout the fatigue testing, so as to prevent the loss of moisture occurring during the fatigue test due to test artifacts such as specimen heatup, etc. The overall individual fatigue specimen test results are given in Appendix II to this report (see Table VIII and Figures 27 to 38).

Figure 2 shows the behavior of T-300 Graphite/1014 S-Glass/Narmco 5208 hybrid composites with a 1:1 (graphite-to-glass) ratio before and after exposure to the high-humidity environment described in Section 3.0. This data was the only data showing a decrease in the fatigue resistance with prior moisture saturation. For most cyclic life levels a decrease of from 5 to 10% was shown. Here the outer layers of the 0° hybrid composite were glass. In an earlier study (1) a similar comparison for 0° hybrid (also T-300 Graphite/1014 S-Glass/Narmco 5208) but with the graphite on the outer plies, a 10% increase in fatigue resistance was shown for a 50% graphite 0° hybrid with moisture absorbtion. Moisture weight gains were of the order of 1.0 to 1.2% by weight in the current study. This corresponded closest to those levels in reference 1 at 1000 hrs/120°F/98% RH. Furthermore the wet stresses at every cyclic life level for both stacking sequences, namely

$$[\mathrm{OL/OR/OL/O_2R/OL/OR/OL}] \text{ - current study}$$

and $[OR/OL/OR/O_2L/OR/OL/OR]$ ~ref 1

were virtually identical at the 1% moisture absorbed level. The two unconditioned fatigue resistances varied considerably with that of the current study being vastly superior. Such comparisons of unconditioned samples may be of academic interest only however.

Figure 3 presents a comparison of the dry versus wet fatigue resistance for a 2:1 (graphite-to-glass) hybrid composite. Again the glass layers are on the outside of the composite. The wet fatigue resistance here is about 10% greater than the corresponding dry strength. A comparison of this stacking sequence,

$[OL/O_4R/OL]$

with that in reference 1,

$[OR/OL/O_2R/OL/OR]$

shows that the wet hybrid at the 1% moisture absorbed level performs about the same for both stacking sequences. However, the dry fatigue resistances are considerably different. One characteristic appears in both studies. More curvature in the fatigue S-N diagram is apparent for the dry composites than in the case of the wet composites.

Figure 4 shows a comparison of a high glass percentage hybrid in both the wet and dry condition. Here the difference is striking with approximately a 25% increase in fatigue resistance wet at cyclic life levels of 10^6 to 10^7 cycles. Furthermore the wet high cycle fatigue strengths of the 33% graphite hybrids are only about 5% less than those for wet 67% graphite hybrids. Cost savings would be more significant than for the highly directional composites.

For the 50% (graphite) quasi-isotropic composites the outer plies were ±45° glass. There was no essential difference in the fatigue resistances of the wet or dry composites as is clearly shown in Figure 5. Again a comparison with the results of reference 1 were made. The two stacking sequences were:

$[\pm 45L/0R/90_2R/0R/\mp 45L]$ ~ current study

and $[0R/\pm 45L/90_2R/\pm 45L/0R]$ - reference 1

The results showed no difference in fatigue behavior wet or dry or in either stacking sequence. This particular composite type had the most consistent behavior for the two stacking sequences either dry or at the 1% moisture absorbed level. Since the 1:1 quasi-isotropic composite delaminated severely under fatigue the conclusions of reference 1, namely that under moisture attack the matrix is most seriously affected and early so that the 0° plies which are all graphite begin to assume the principal share of the cyclic tensile loads remains viable. Furthermore, this load redistribution occurs regardless of the outer-inner location of the 0° graphite plies.

Figures 6 and 7 present similar results for 2:1 and 1:2 (graphite-to-glass ratios) hybrid composites of the quasi-isotropic types. The 2:1 quasi-isotropic hybrid can also be compared with another stacking sequence. Thus;

$[\pm 45L/0R/90_2R/0_2R/90_2R/0R/\mp 45L]$

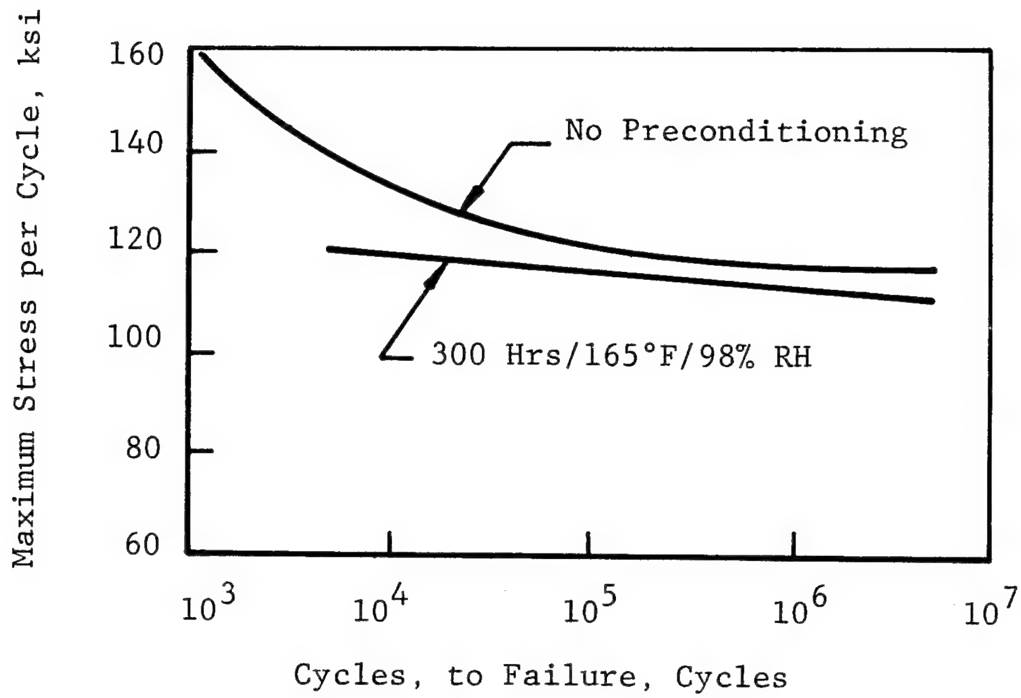
of the present study, and

$[0R/90R/\pm 45L/90R/0_2R/90R/\mp 45L/90R/0R]$

of reference 1 both show an increase of 8% wet fatigue strengths over the dry fatigue S-N diagrams. Furthermore the 1% absorbed moisture levels for the two stacking sequences show approximately the same fatigue diagrams (less than 5% differences).

The wet 1:2 hybrid results shown in Figure 7 indicate a 25% loss in load carrying capability from the 2:1 hybrid shown in Figure 6. However, for the same 12 plies of material only 4 are graphite in the 1:2 case whereas 8 were graphite in the 2:1 case. It is also important that only two of the four 0° plies in Figure 7 are graphite while in Figure 6 all four 0° plies were graphite. Again considerable cost savings might be realized using 67% glass hybrid composites.

The static tensile mechanical properties of the hybrid composites after fatigue cycling are shown in Figures 8-15. The stress levels selected for the fatigue cycling were those corresponding to failure above 2×10^6 cycles. The residual elastic modulus generally remained constant over the span from 10^3 to 10^7 cycles. In addition all of the 0° hybrid composites, i.e., 33%, 50% and 67% graphite ratios showed a constant residual Poisson's ratio ν with cyclic history. In general, the residual strengths decreased as a result of prior stress cycling, greater strength reductions being noted for the wet hybrids than for the dry (unconditioned) composites. For all quasi-isotropic hybrids, the residual Poisson's ratio increased as a function of prior stress cycling. This increase was also noted in reference 1 and seems to be a verified anomaly in the behavior of the quasi-isotropic hybrid (and baseline (100%) graphite) composites.



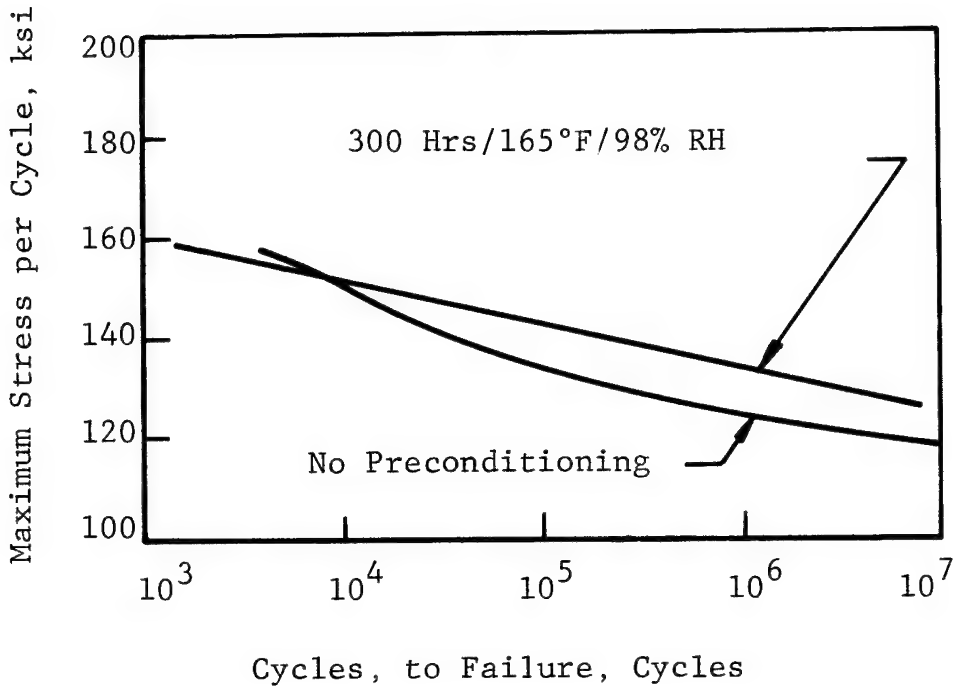
Orientation: [OL/OR/OL/O_2R/OL/OR/OL]

Temperature: 75°F

Stress Cycle: R = 0.1/T = 75°F/ϕ = 30 Hertz

Percentage Graphite: 50%, by plies

FIGURE 2 Comparative Fatigue S-N Behavior for S-Glass/T300 Graphite/Narmco 5208 Hybrid Composites Before and After Exposure To High Humidity Environment.



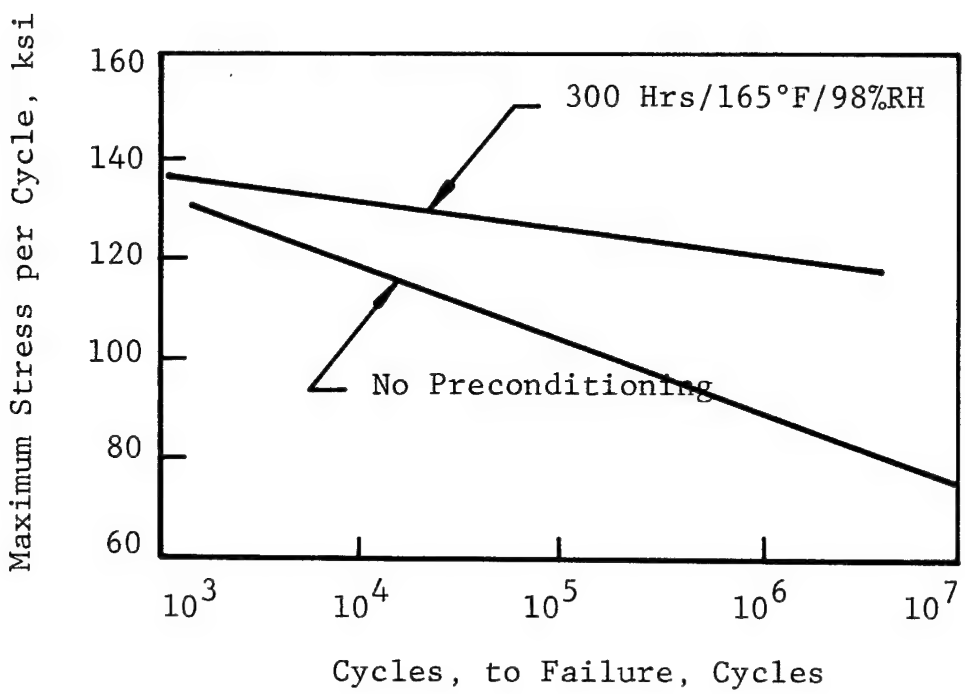
Orientation: [OL/O_4R/OL]

Temperature: 75°F

Stress Cycle: R = 0.1/T = 75°F/ϕ = 30 Hertz

Percentage Graphite: 67%, by plies

FIGURE 3 Comparative Fatigue S-N Behavior For S-Glass/T300 Graphite/Narmco 5208 Hybrid Composites Before and After Exposure To High Humidity Environment.



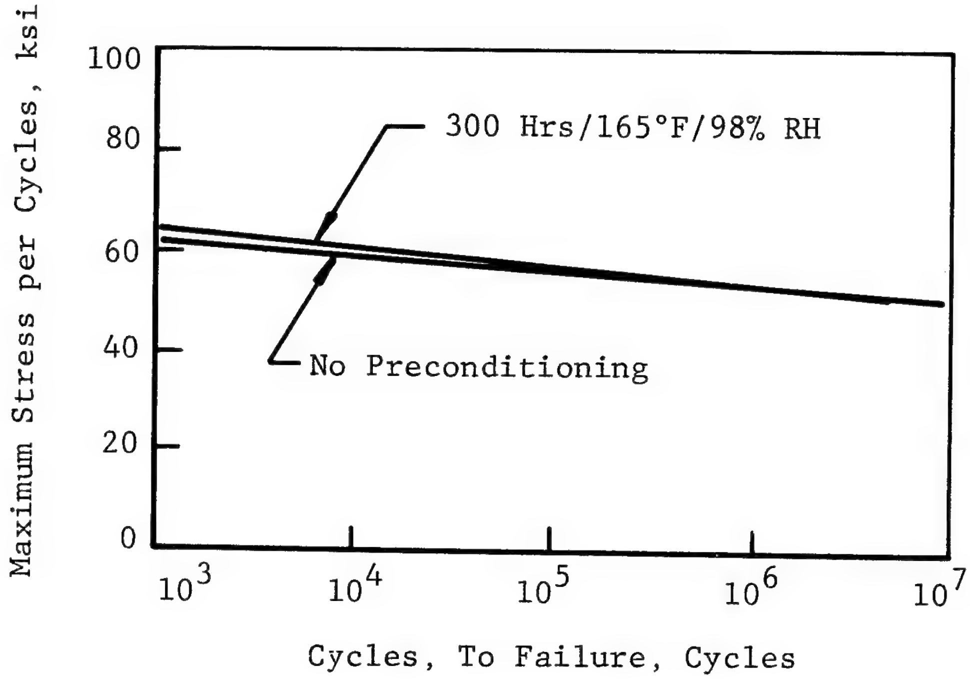
Orientation: $[0_2L/0_2R/0_2L]$

Temperature: 75°F

Stress Cycle: R = 0.1/T = 75°F/ϕ = 30 Hertz

Percentage Graphite: 33%, by plies

FIGURE 4 Comparative Fatigue S-N Behavior for S-Glass/T300 Graphite/Narmco 5208 Hybrid Composites Before and After Exposure To High Humidity Environment.



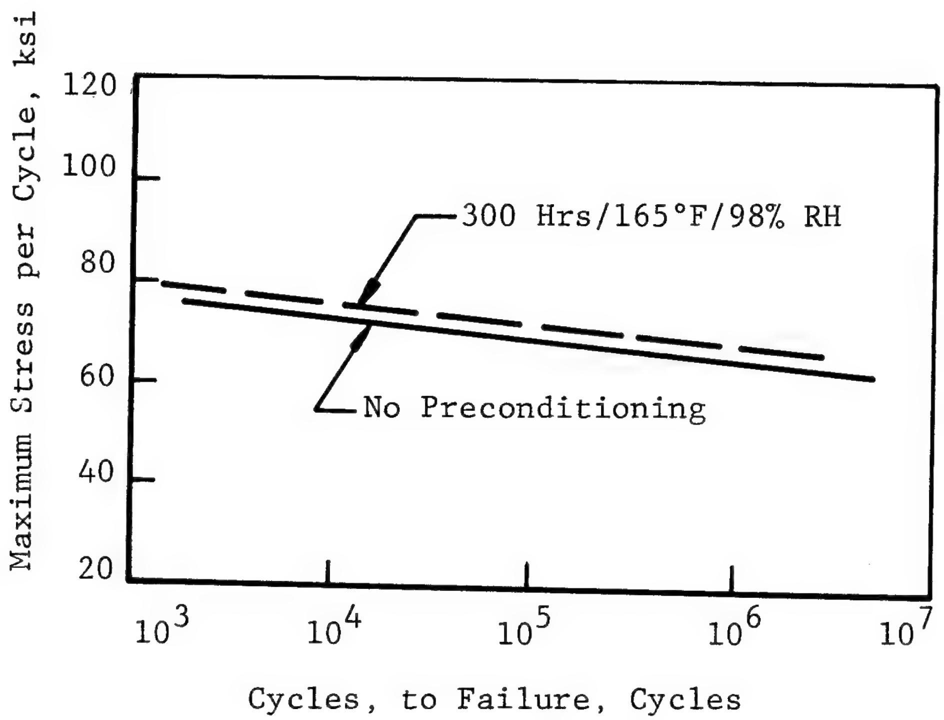
Orientation: $[\pm45L/0R/90_2R/0R/\mp45L]$

Temperature: 75°F

Stress Cycle: R = 0.1/T = 75°F/ϕ = 30 Hertz

Percentage Graphite: 50%, by plies.

FIGURE 5 Comparative Fatigue S-N Behavior For S-Glass/T300 Graphite/Narmco 5208 Hybrid Composites Before and After Exposure To High Humidity Environment.



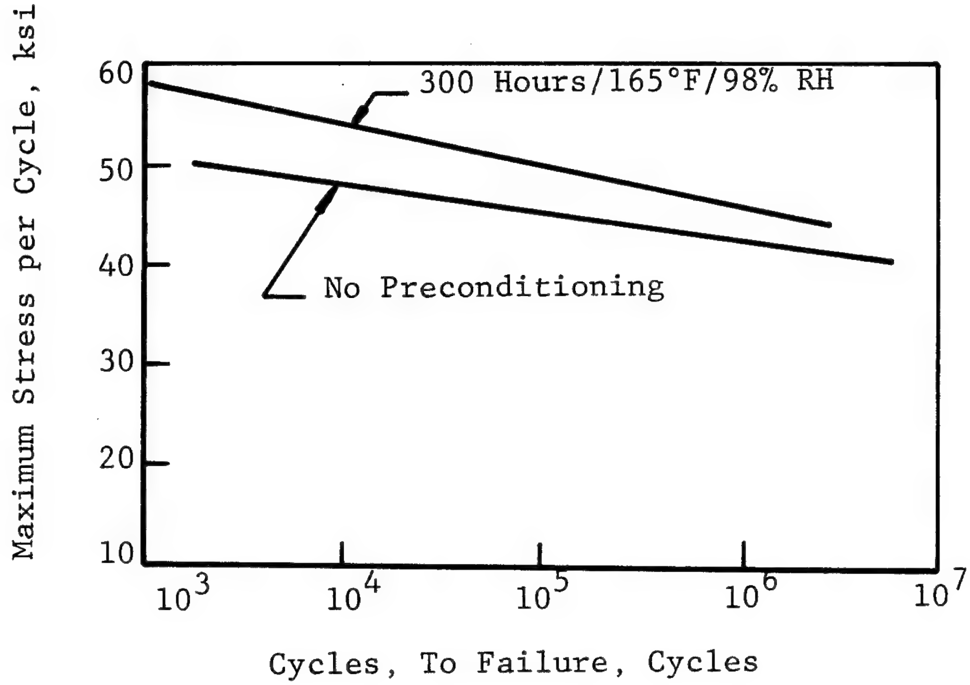
Orientation: [$\pm$45L/OR/90_2R/0_2R/90_2R/OR/$\mp$45L]

Temperature: 75°F

Stress Cycle: R = 0.1/T = 75°F/ϕ = 30 Hertz

Percentage Graphite: 66%, by plies

FIGURE 6 Comparative Fatigue S-N Behavior For S-Glass/T300 Graphite/Narmco 5208 Hybrid Composites Before And After Exposure To High Humidity Environments.



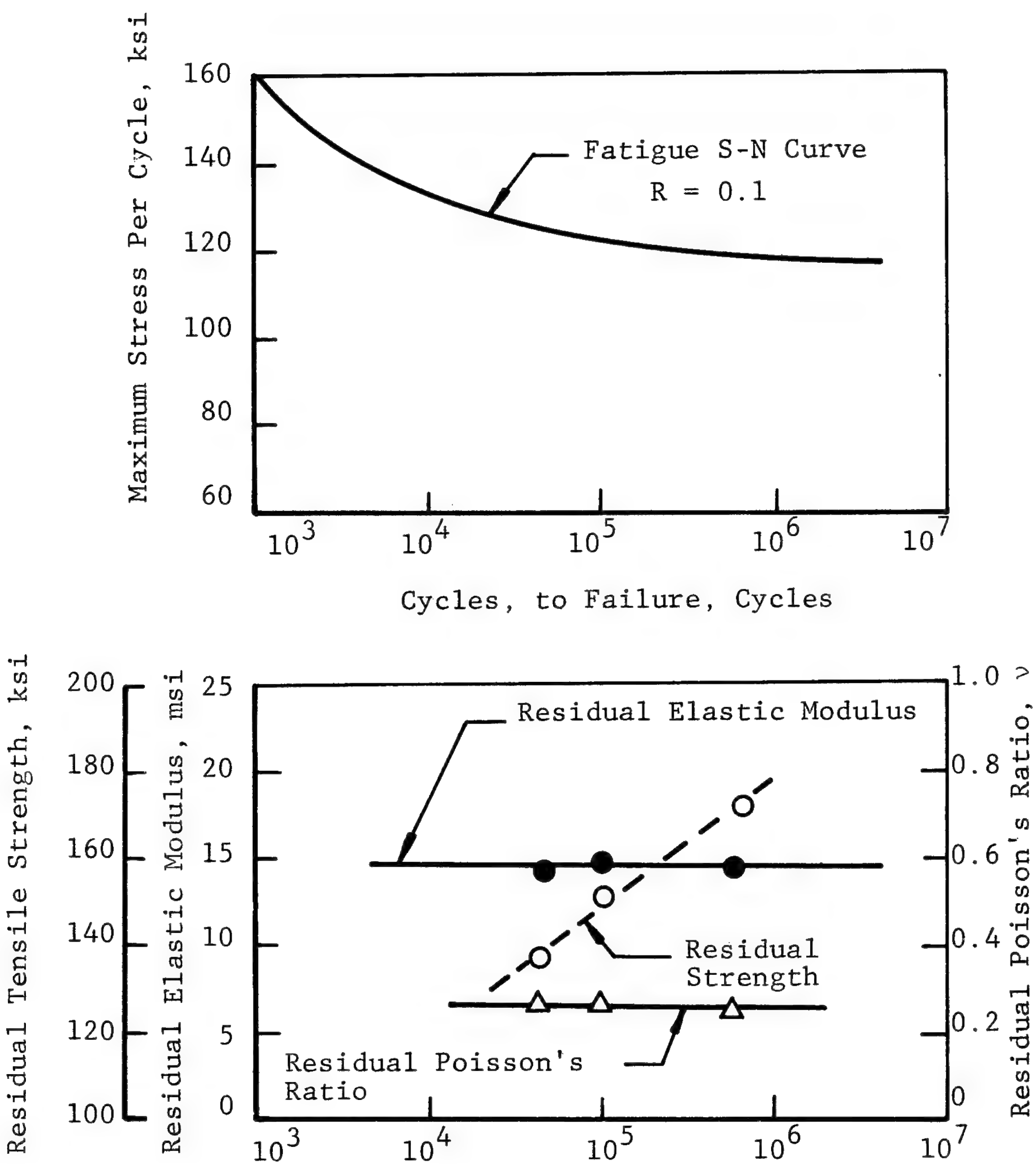
Orientation: [$\pm$45L/OR/90R/90L/O_2L/90L/90R/OR/$\mp$45L]

Temperature: 75°F

Stress Cycle: R = 0.1/T = 75°F/ϕ = 30 Hertz

Percentage Graphite: 33%, by plies

FIGURE 7 Comparative Fatigue S-N Behavior For S-Glass/T300 Graphite/Narmco 5208 Hybrid Composites Before and After Exposure To High Humidity Environments.

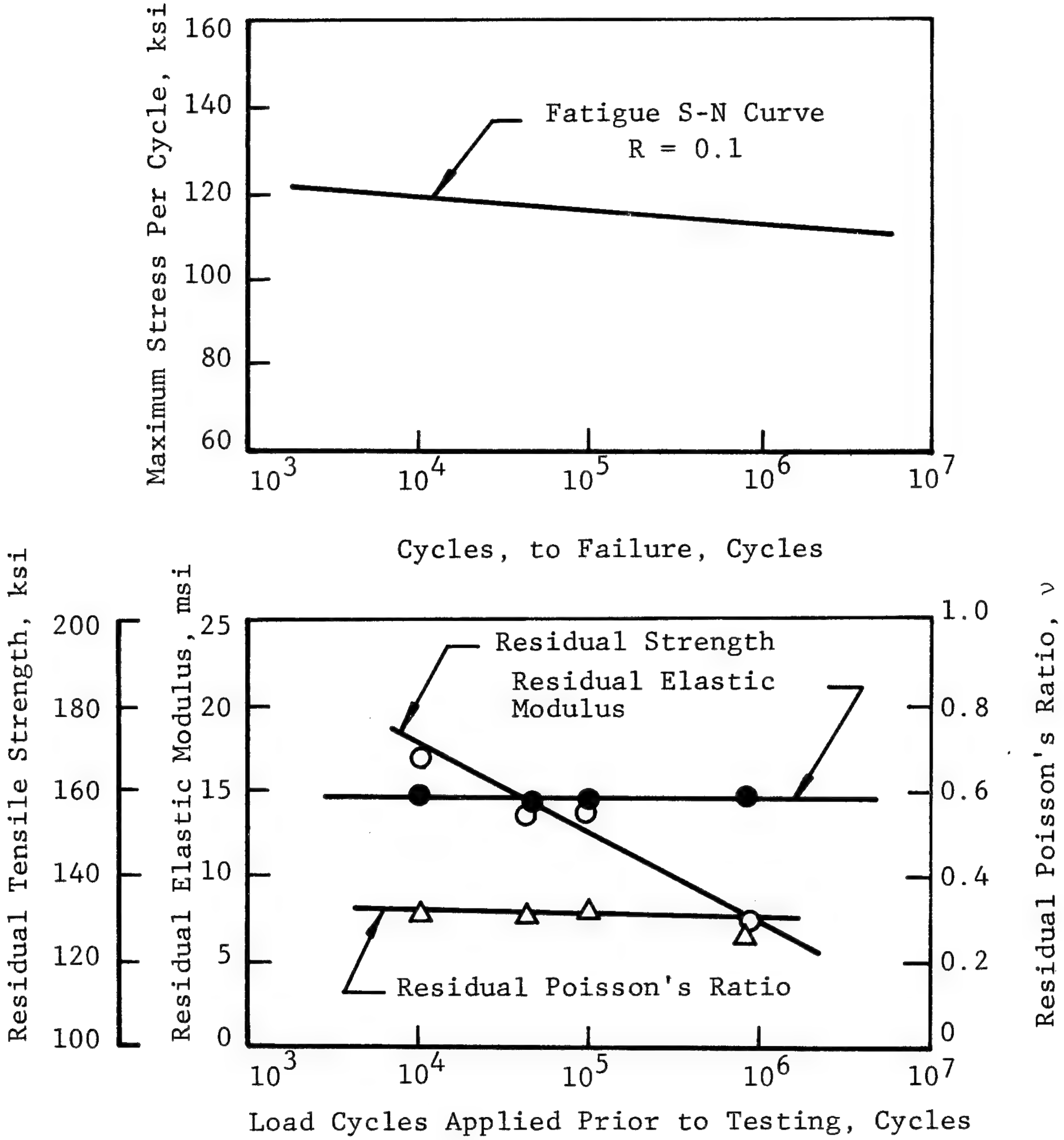


Material: [OL/OR/OL/O_2R/OL/OR/OL]

Cyclic Stress Level : 110 ksi

Prior Conditioning : None

FIGURE 8 Residual Strength, Elastic Modulus and Poisson's Ratio for Composite Material (ϕ=1800 cpm, R=0.1, T=75°F, Orientation, Stress Level and Prior Conditioning as noted), 50% Graphite By Plies.

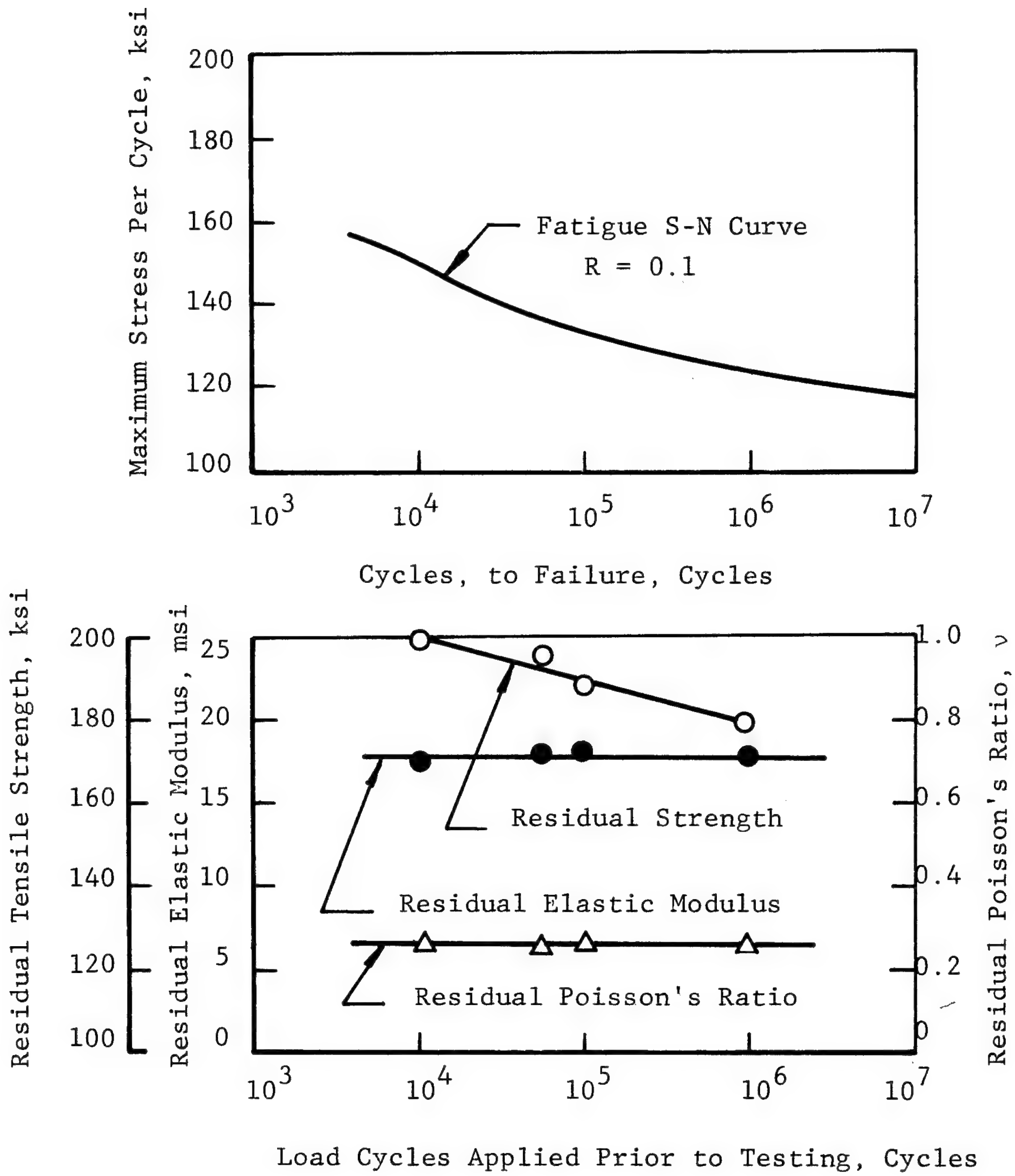


Material: [OL/OR/OL/O_2R/OL/OR/OL]

Cyclic Stress Level: 110 ksi

Prior Conditioning:: 165°F/98% RH/300 Hours

FIGURE 9 Residual Strength, Elastic Modulus and Poisson's Ratio for Composite Material (ϕ=1800 cpm, R=0.1, T=75°F, Orientation, Stress Level and Prior Conditioning as Noted), 50% Graphite By Plies.

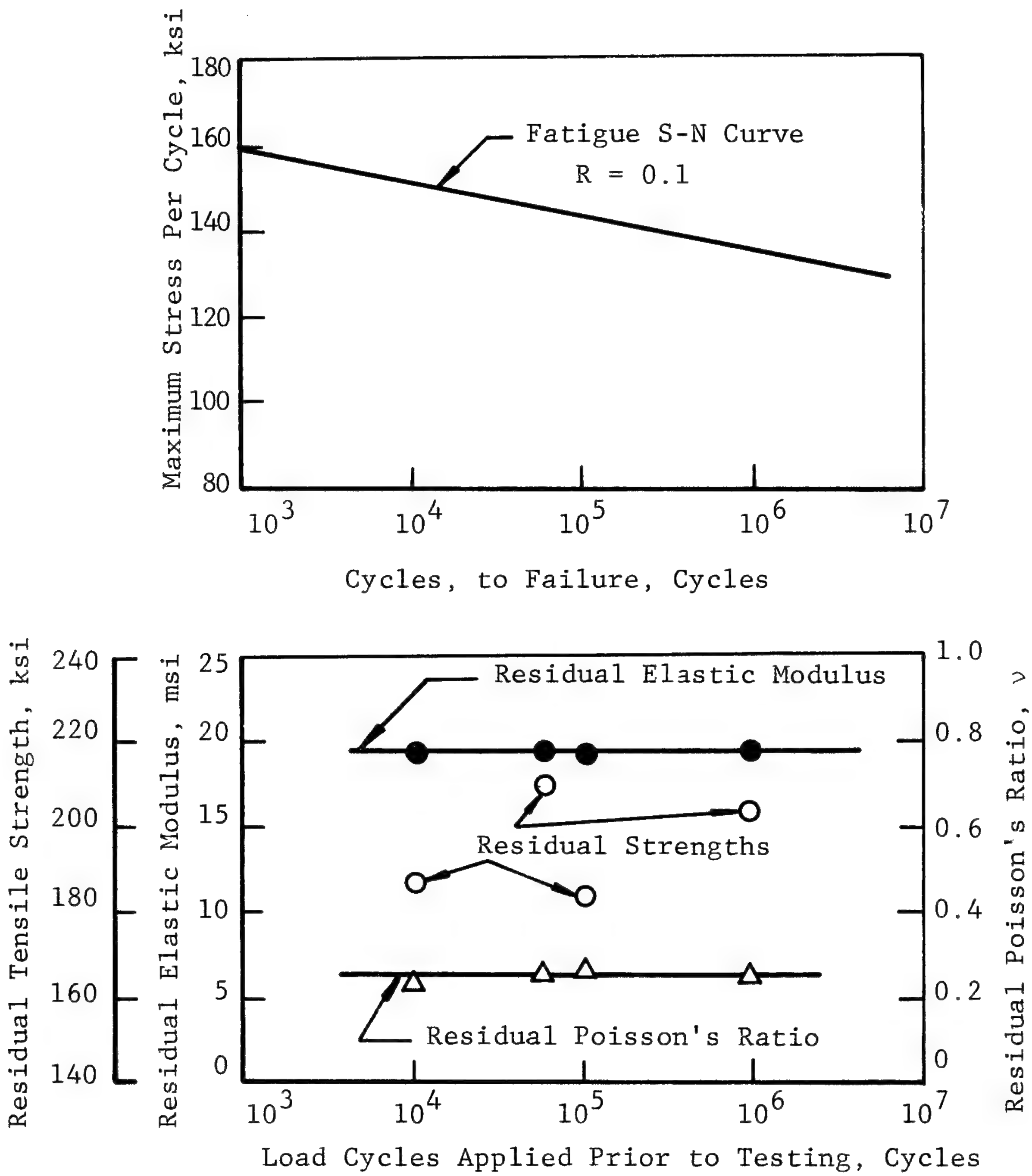


Materials: [OL/0_4R/OL]

Cyclic Stress Level: 110 ksi

Prior Conditioning: None

FIGURE 10 Residual Strength, Elastic Modulus and Poisson's Ratio for Composite Material (ϕ=1800 cpm, R=0.1, T=75°F, Orientation, stress Level and Prior Conditioning as Noted), 67% Graphite by Plies.

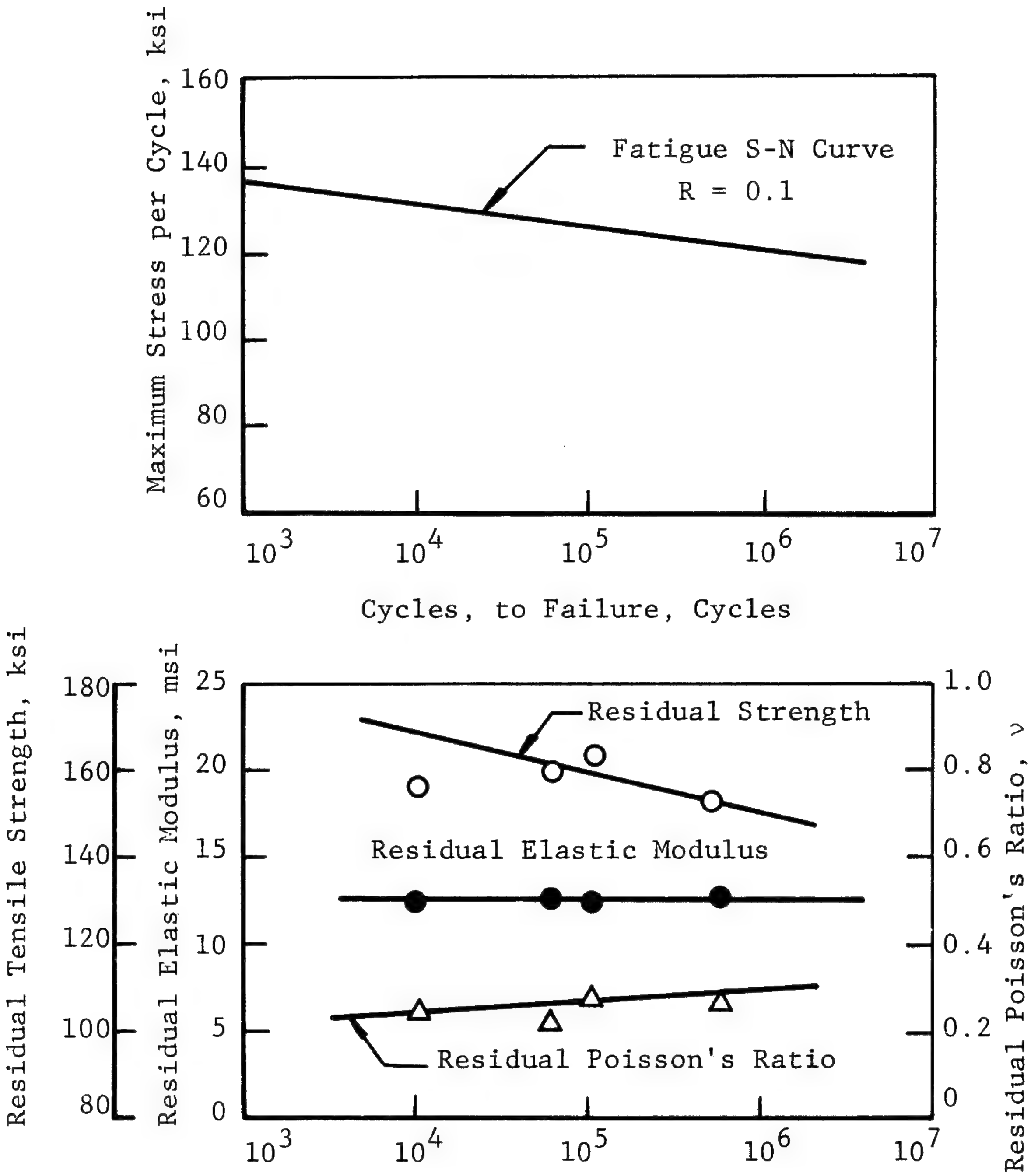


Material: $[OL/O_4R/OL]$

Cyclic Stress Level: 135 ksi

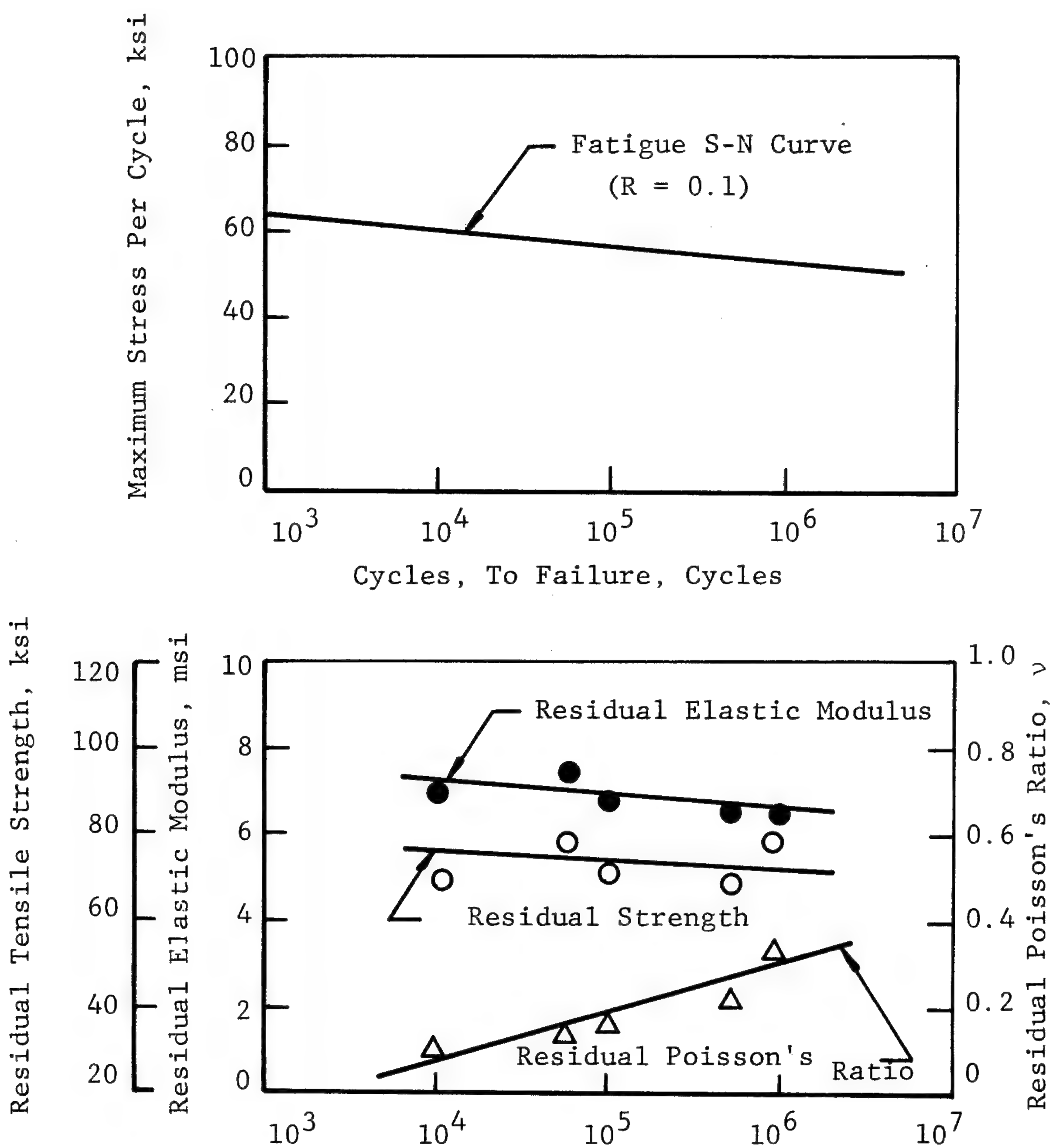
Prior Conditioning: 165°F/98% RH/300 Hours

FIGURE 11 Residual Strength, Elastic Modulus and Poisson's Ratio for Composite Material (ϕ=1800 cpm, R=0.1 T=75°F, Orientation, Stress Level and Prior Conditioning as Noted), 67% Graphite by Plies.



Material: $[0_2L/0_2R/0_2L]$
Cyclic Stress Level: 114 ksi
Prior Conditioning: 165°F/98% RH/300 Hours

FIGURE 12 Residual Strength, Elastic Modulus and Poisson's Ratio for Composite Material (ϕ=1800 cpm, R=0.1, T=75°F, Orientation, Stress Level And Prior Conditioning as Noted), 33% Graphite by Plies.

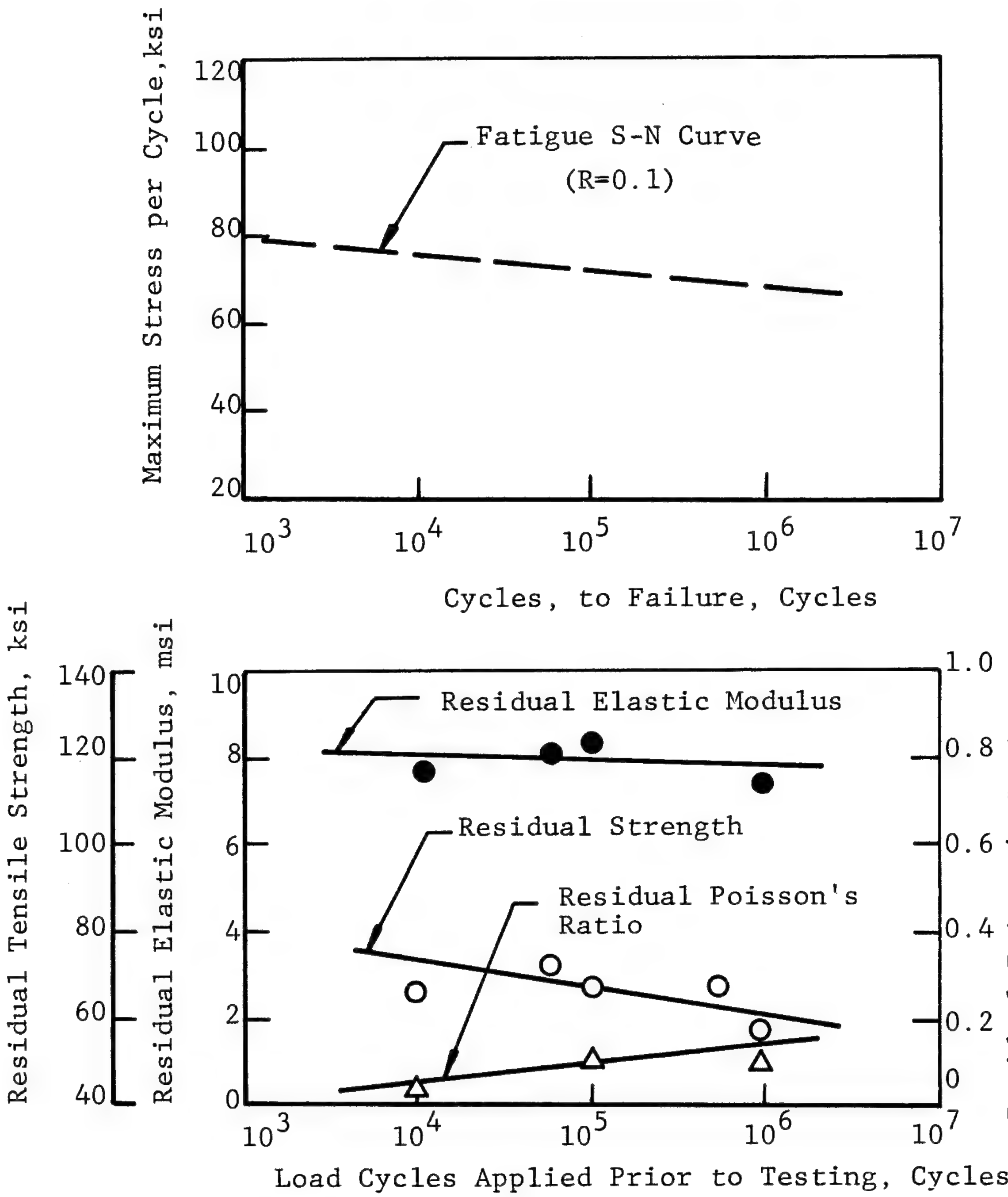


Material: [±45L/OR/90_2R/OR/∓45L]

Cyclic Stress Level: 52 ksi

Prior Conditioning: 165°F/98% RH/300 Hours

FIGURE 13 Residual Strength, Elastic Modulus and Poisson's Ratio for Composite Material (ϕ=1800 cpm, R=0.1 T=75°F, Orientation, stress Level and Prior Conditioning as Noted), 50% Graphite by Plies.

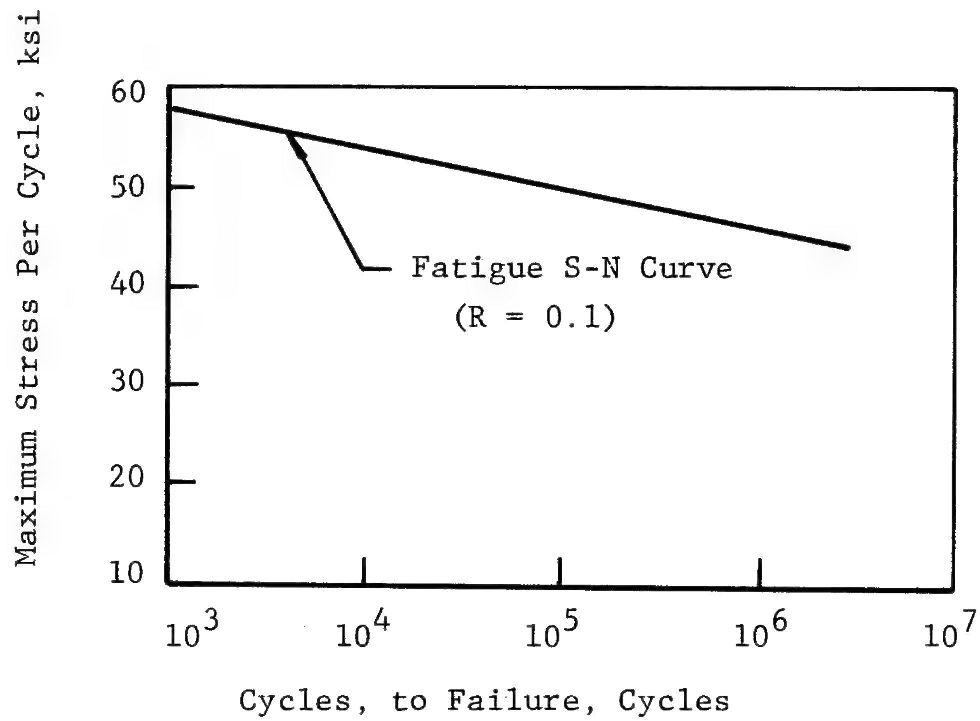


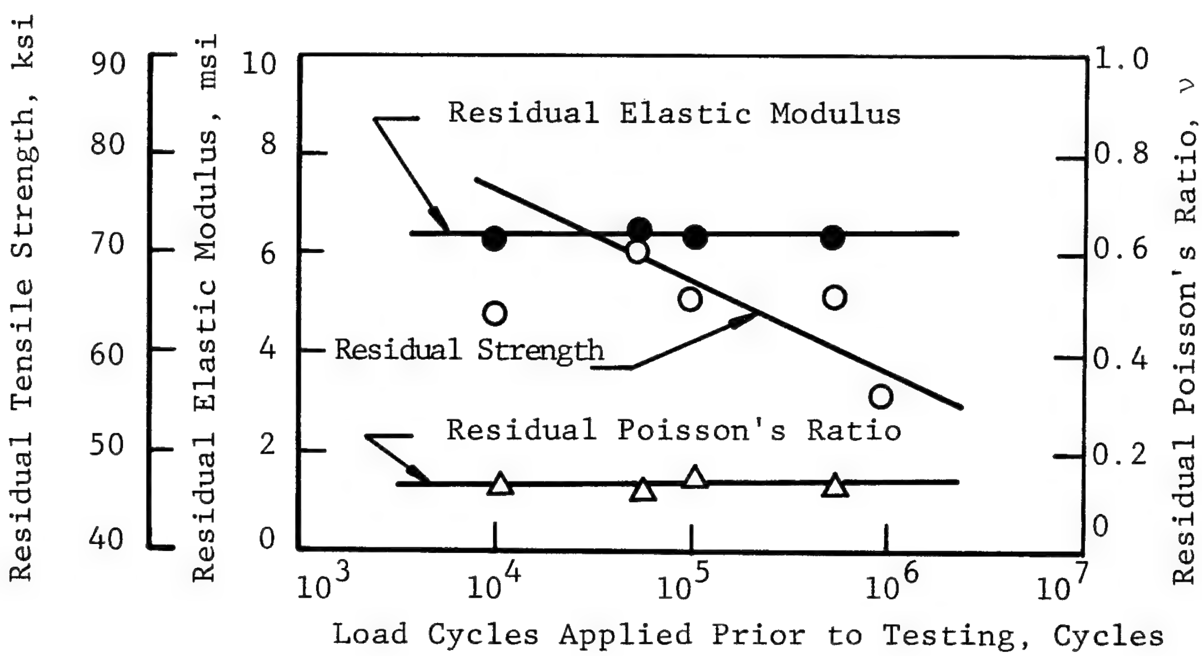
Material: $[\pm 45L/0R/90_2R/0_2R/90_2R/0R/\pm 45L]$

Cyclic Stress Level: 65 ksi

Prior Conditioning: 165°F/98% RH/300 Hours

FIGURE 14 Residual Strength, Elastic Modulus and Poisson's Ratio for Composite Material (ϕ=1800 cpm, R=0.1, T=75°F, Orientation, Stress Level and Prior Conditioning as Noted), 67% Graphite by Plies.





Material: [±45L/0R/90R/90L/0_2L/90L/90R/0R/±45L]

Cyclic Stress Level: 42 ksi

Prior Conditioning: 165°F/98% RH/300 Hours

FIGURE 15 Residual Strength, Elastic Modulus and Poisson's Ratio for Composite Material (ϕ=1800 cpm, R=0.1 T=75°F, Orientation, Stress Level and Prior Conditioning as Noted), 33% Graphite by Plies.

SECTION V

5.0 RESPONSE OF HYBRID COMPOSITES TO PROLONGED LOADING

The response of hybrid composites to prolonged tensile loading was measured using specimens identical to those employed in the tensile fatigue studies described in Section 4.0. Creep strain versus time curves for several hybrid composites were generated at several stress levels.

The equipment shown in Figure 16 was utilized. Each stand was located on a vibration free floor. For achieving the required levels of loading, a load multiplication arrangement was provided by an appropriate ratio of loading arm (L.A.) to reaction arm (R.A.). For example, a loading of 300 lbs. on the load platform provided a force of 3000 lbs. on the specimen when the L.A./R.A. ratio was kept at 10. Because of the large creep stresses needed, the ratio was maintained at 10:1 throughout the testing. An electric timer, triggered on each stand at the start of loading and shut off at specimen failure by a microswitch recorded times to failure.

The specimen was aligned in the grips prior to mounting on the creep stand. The jig consisted of a metal base plate with indentations to accomodate the specimen grips including the bolts. The grips were first placed on the base plate and located appropriately over the indentations. A pair of suitably located pins aligned the specimen side parallel to the line of axial bolts. After this alignment, the grip bolts were tightened. During the tightening process, the specimen was prevented from twisting by an angle section attached to the base plate.

A multi-channel data acquisition system was used for

monitoring and recording the strains in several specimens simultaneously. When a specimen failed, the loading arm triggered the microswitch which turned off the timer thus recording the time at failure from the beginning of the loading.

Each stand was calibrated with a specimen of known mechanical properties (2024T4 Aluminum). The appropriate percentages of average ultimate tensile strength levels were computed from the static test data generated for each material in this program. When the specimen was mounted on the stand just prior to loading, a load representing the desired stress level was placed on the loading platform while the platform was supported on a hydraulic jack. The strain gage bridge was then zeroed and the strain indicator balanced. Then the jack was released gently but quickly to bring an instantaneous loading on the specimen. The timer was started simultaneously with the release of the load. Since the timers installed were capable of recording to a tenth of an hour, initial readings of strain were taken with the assistance of a stop watch.

Figures 17-26 present the results of the prolonged loading test program for various hybrid composites. In almost every case the tensile creep strains were small and showed only secondary creep tendencies. None of the composites were captured in the tertiary creep stages. In most cases creep measurements were taken out to 500 hours or more. The all 0° hybrid showed little or no creep strain increase over initial strain out to 500 hours. Approximately 2 to 5% greater strains than initial elastic strains were the general rule. For comparable stress levels (say 125 ksi), the increases were 3%, 8%, 10% over initial elastic strains for the 67%, 50% and 33% graphite (by plies) hybrid composites respectively. For the quasi-isotropic hybrid composites the comparable increases over initial elastic strains were 5%, 10% and 10% respectively for 67%, 50% and 33% graphite percentages.

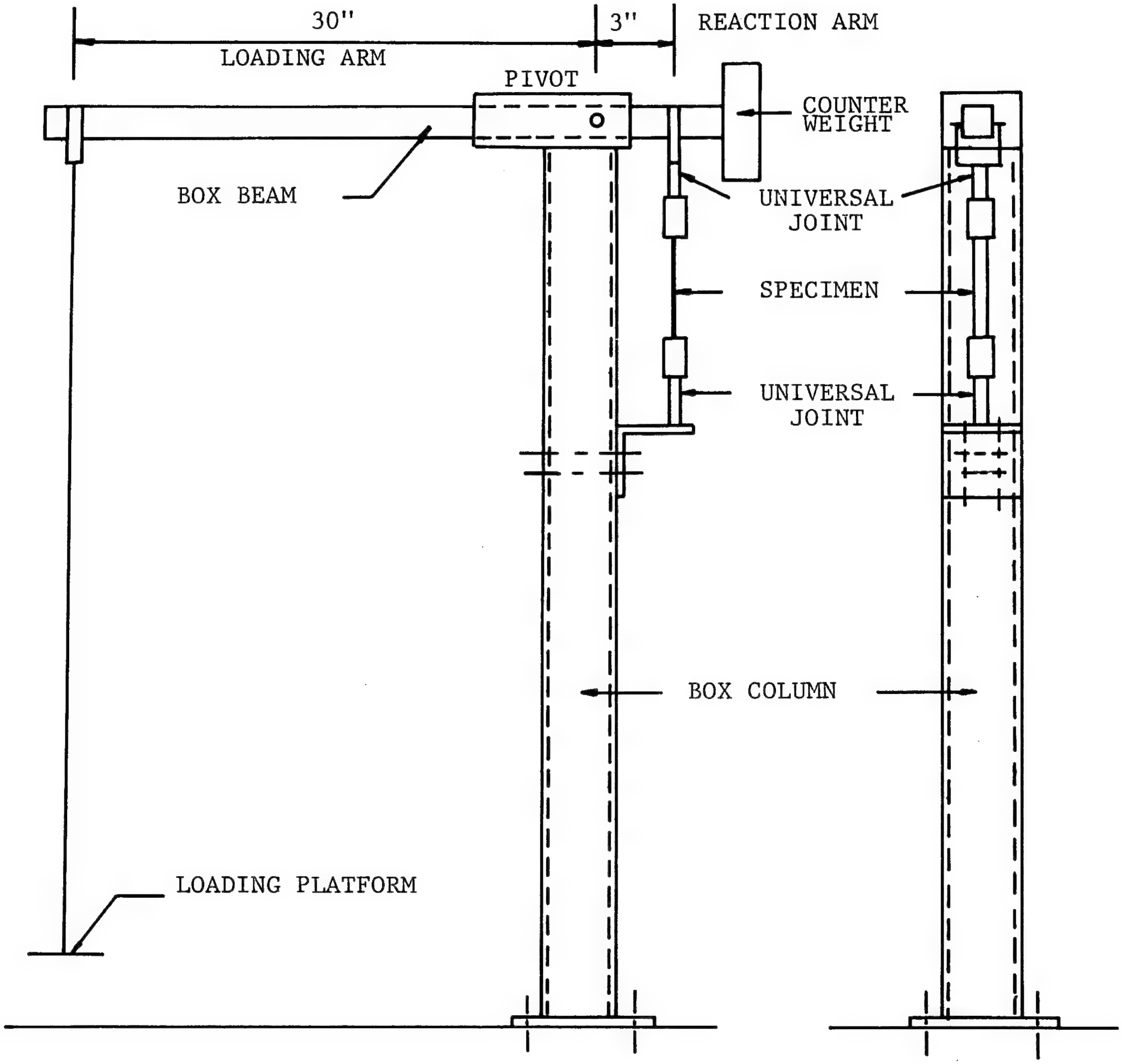


FIGURE 16 SCHEMATIC FOR DEAD LOAD TENSILE CREEP APPARATUS

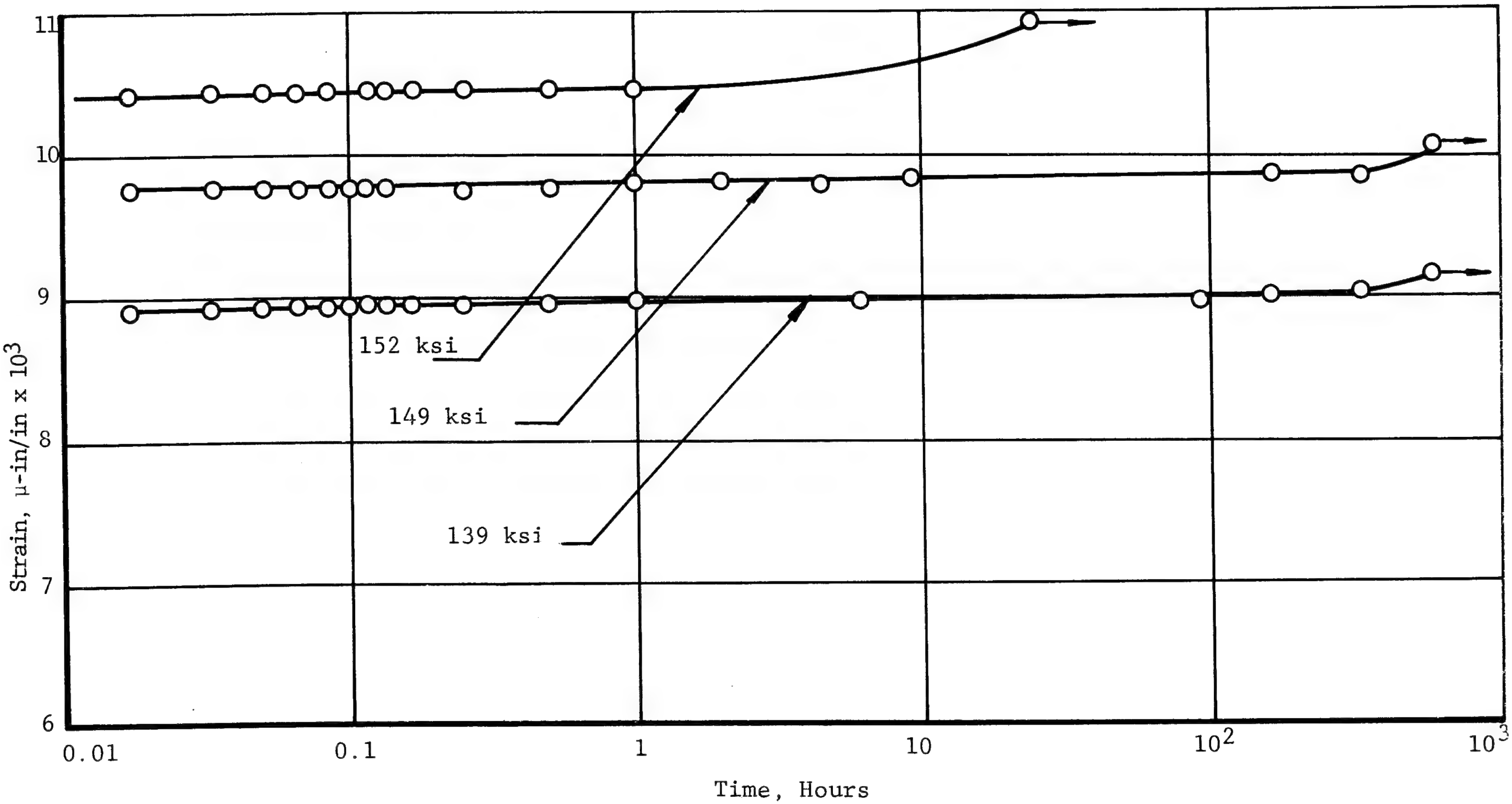


FIGURE 17 CREEP STRAIN VERSUS TIME CURVES FOR $[OL/OR/OL/OR]_s$ T-300 GRAPHITE/ 1014 S-GLASS/NARMCO 5208 HYBRID COMPOSITES TESTED DRY AT T = 70°F.

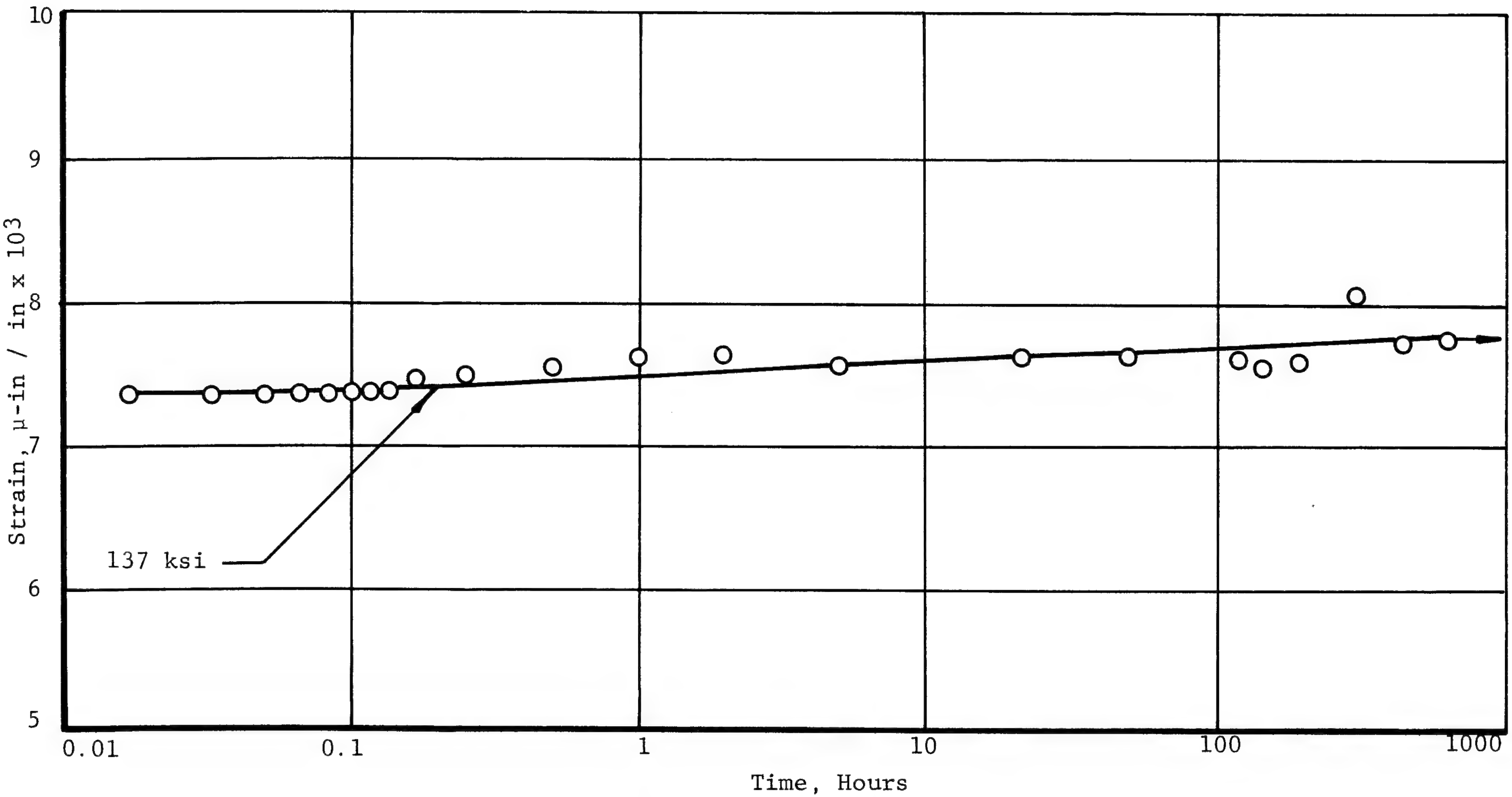


FIGURE 18 CREEP STRAIN VERSUS TIME CURVES FOR [OL/OR/OR/OR/OR/OL] T-300 GRAPHITE/1014S GLASS/ NARMCO 5208 HYBRID COMPOSITES TESTED DRY AT T = 70°F

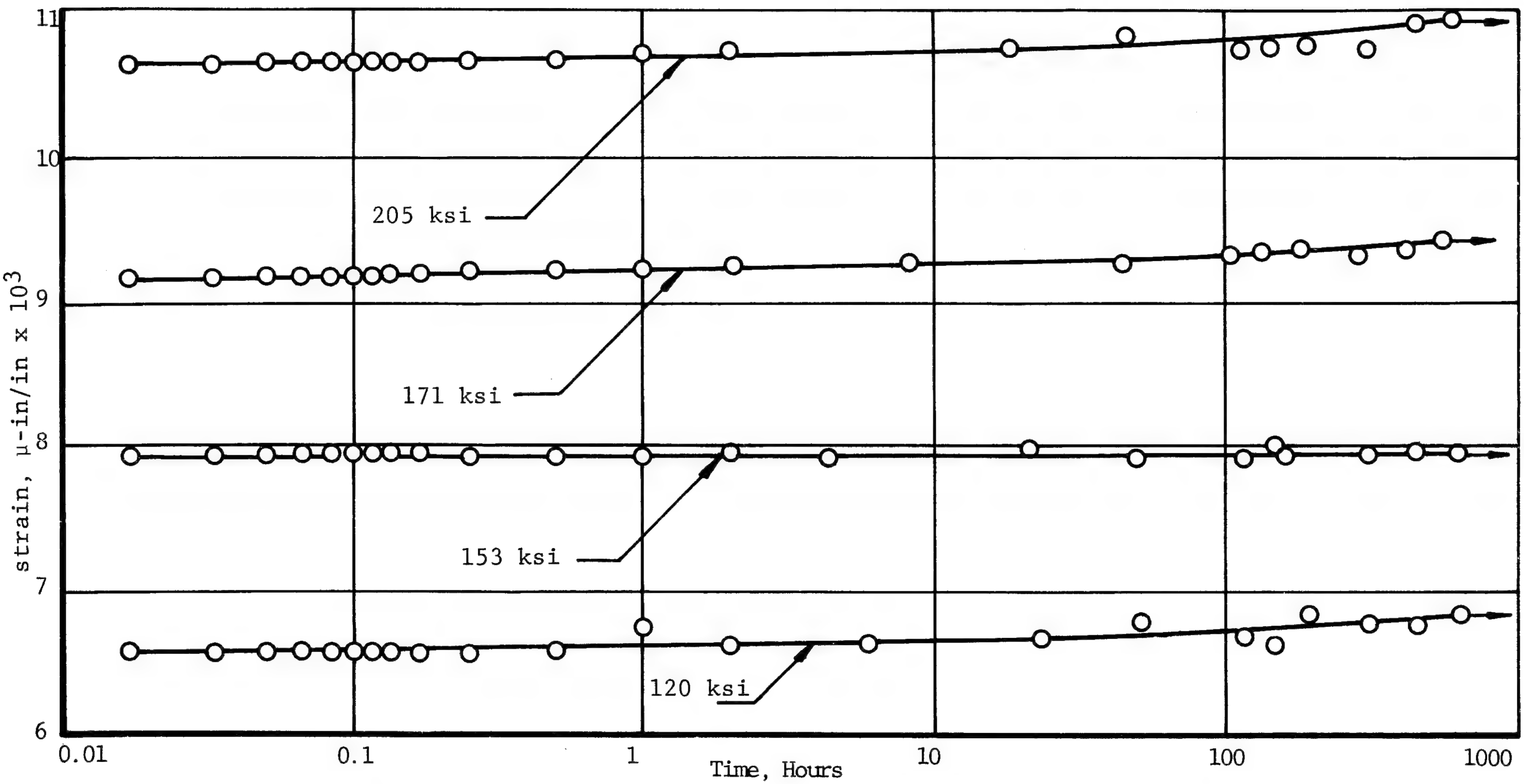


FIGURE 19 CREEP STRAIN VERSUS TIME CURVES FOR [OL/OR/OR/OR/OR/OL] T300 GRAPHITE/ 1014 S-GLASS/NARMCO 5208 HYBRID COMPOSITES TESTED DRY AT T = 70°F

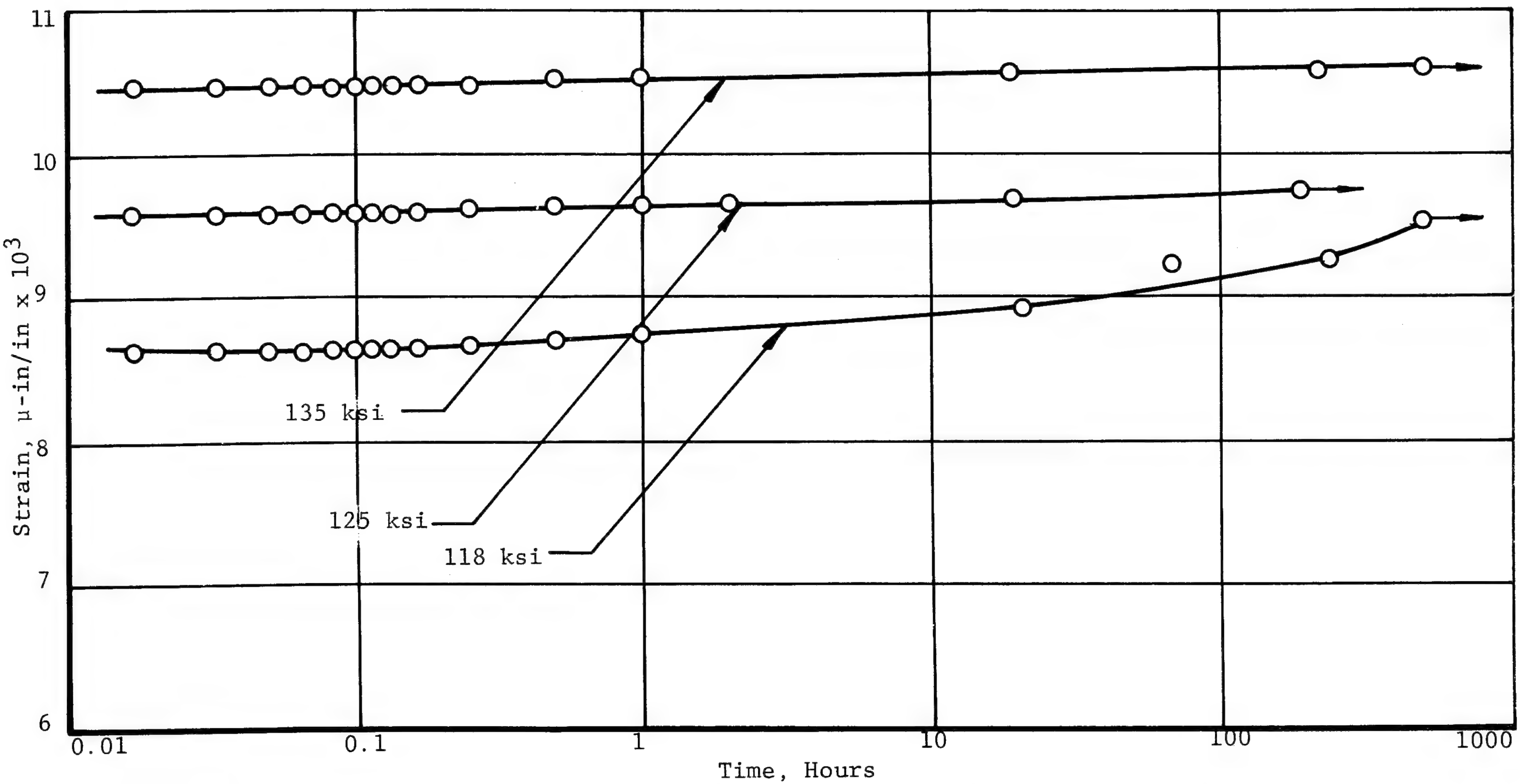


FIGURE 20 CREEP STRAIN VERSUS TIME CURVES FOR [OL/OL/OR/OR/OL/OL] T=300 GRAPHITE/ 1014-S GLASS/NARMCO 5208 HYBRID COMPOSITES TESTED DRY AT T = 70°F.

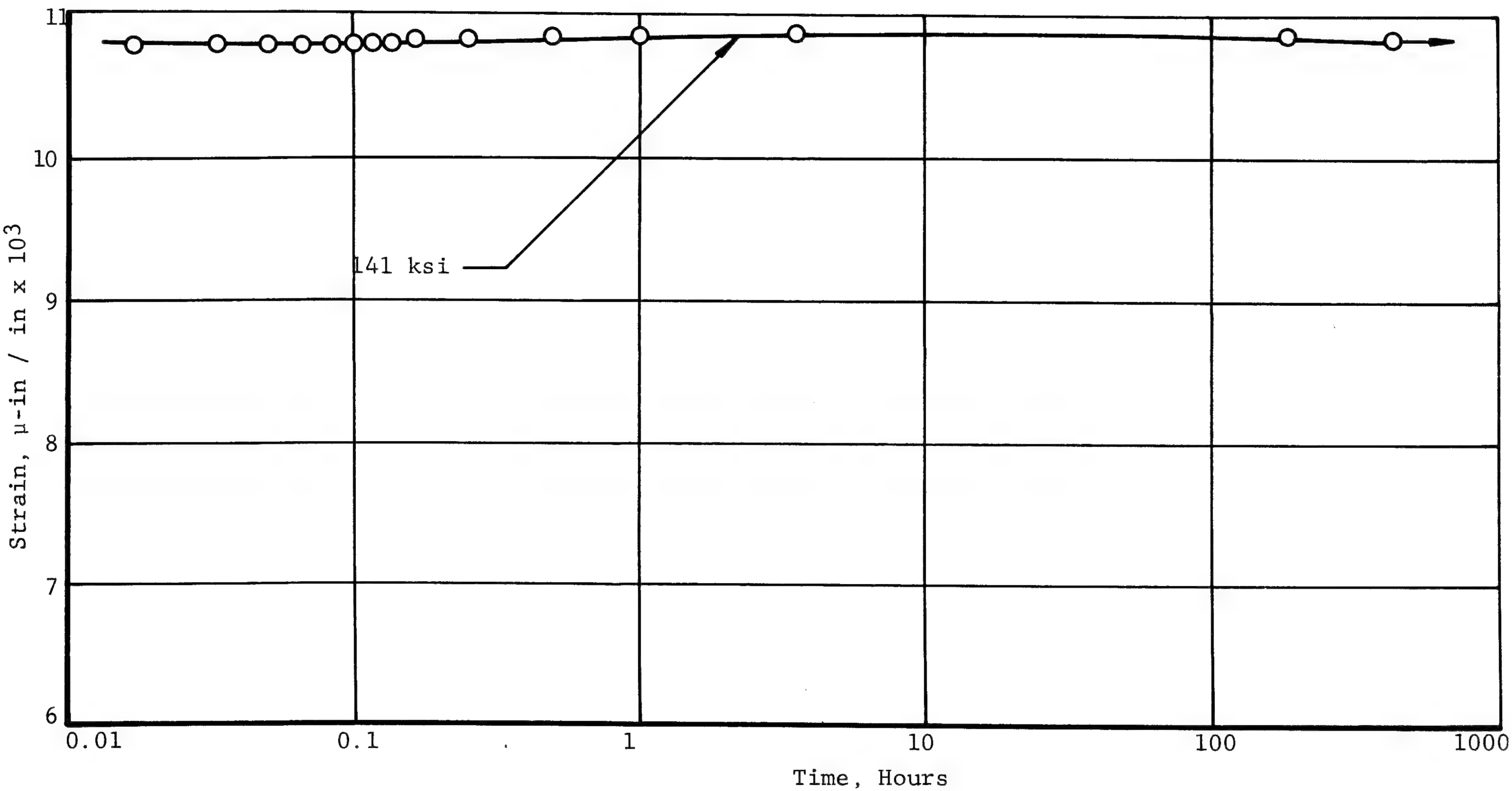


FIGURE 21 CREEP STRAIN VERSUS TIME CURVES FOR [OL/OL/OR/OR/OL/OL] T300 GRAPHITE/ 1014 S-GLASS/NARMCO 5208 HYBRID COMPOSITED TESTED DRY AT T = 70°F.

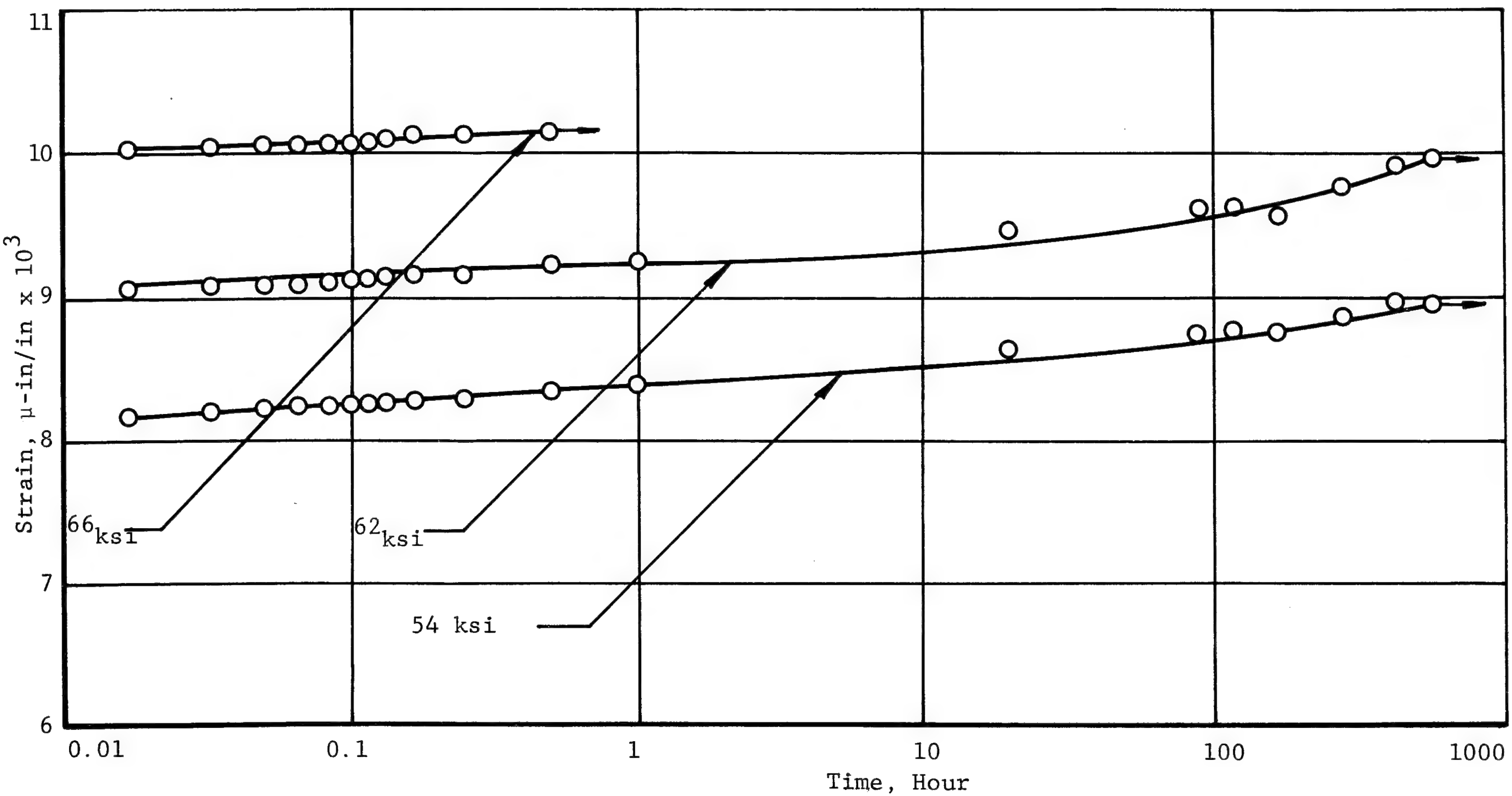


FIGURE 22 CREEP STRAIN VERSUS TIME CURVES FOR [+45L/OR/90R/90R/OR/∓45L] T300 GRAPHITE/1014 S-GLASS/NARMCO 5208 HYBRID COMPOSITES TESTED DRY AT T = 70°F.

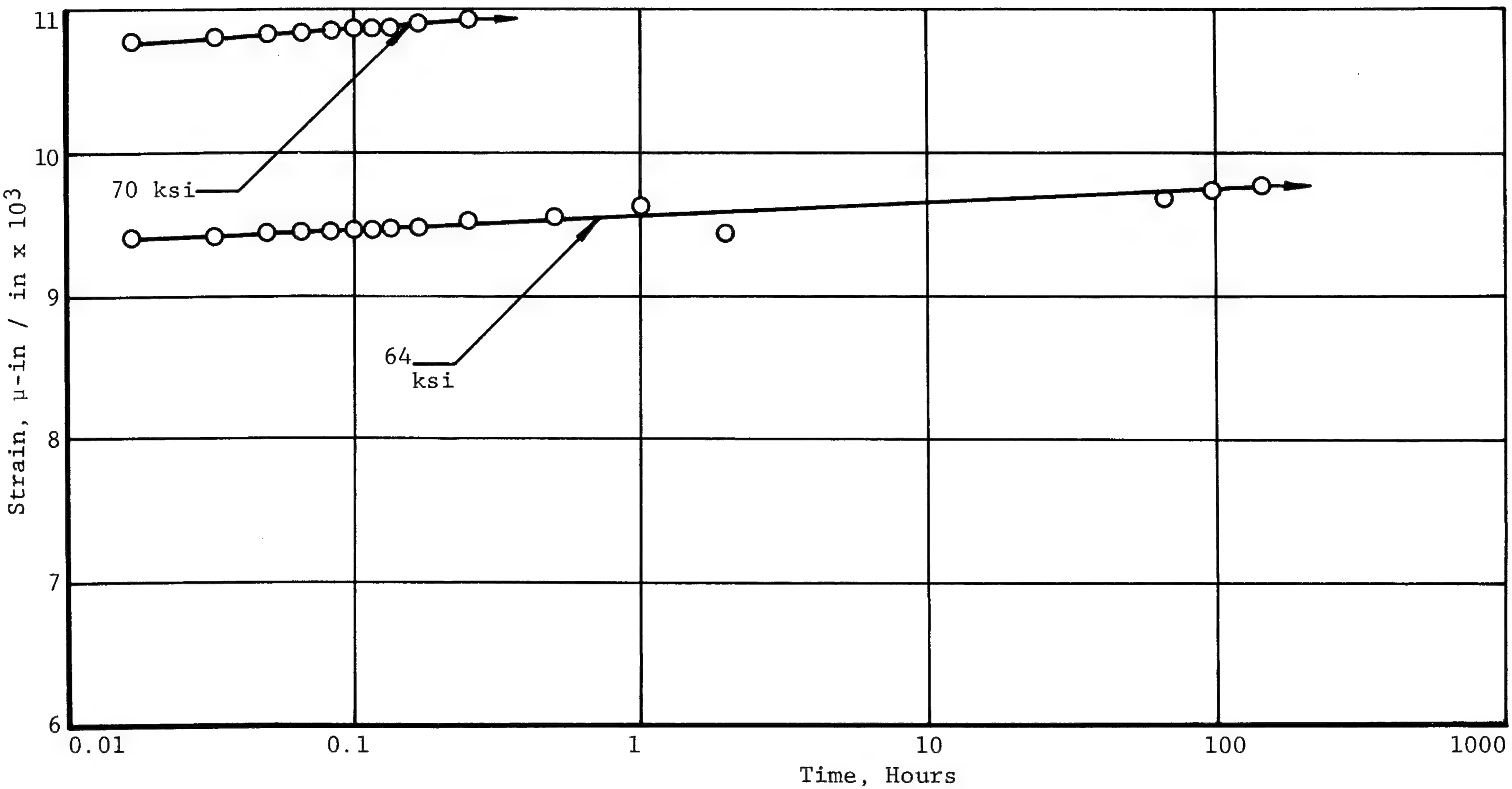


FIGURE 23 CREEP STRAIN VERSUS CURVES FOR [±45L/OR/90R/90R/OR/∓45L] T300 GRAPHITE/1014 S-GLASS/NARMCO 5208 HYBRID COMPOSITES TESTED DRY AT T = 70°F

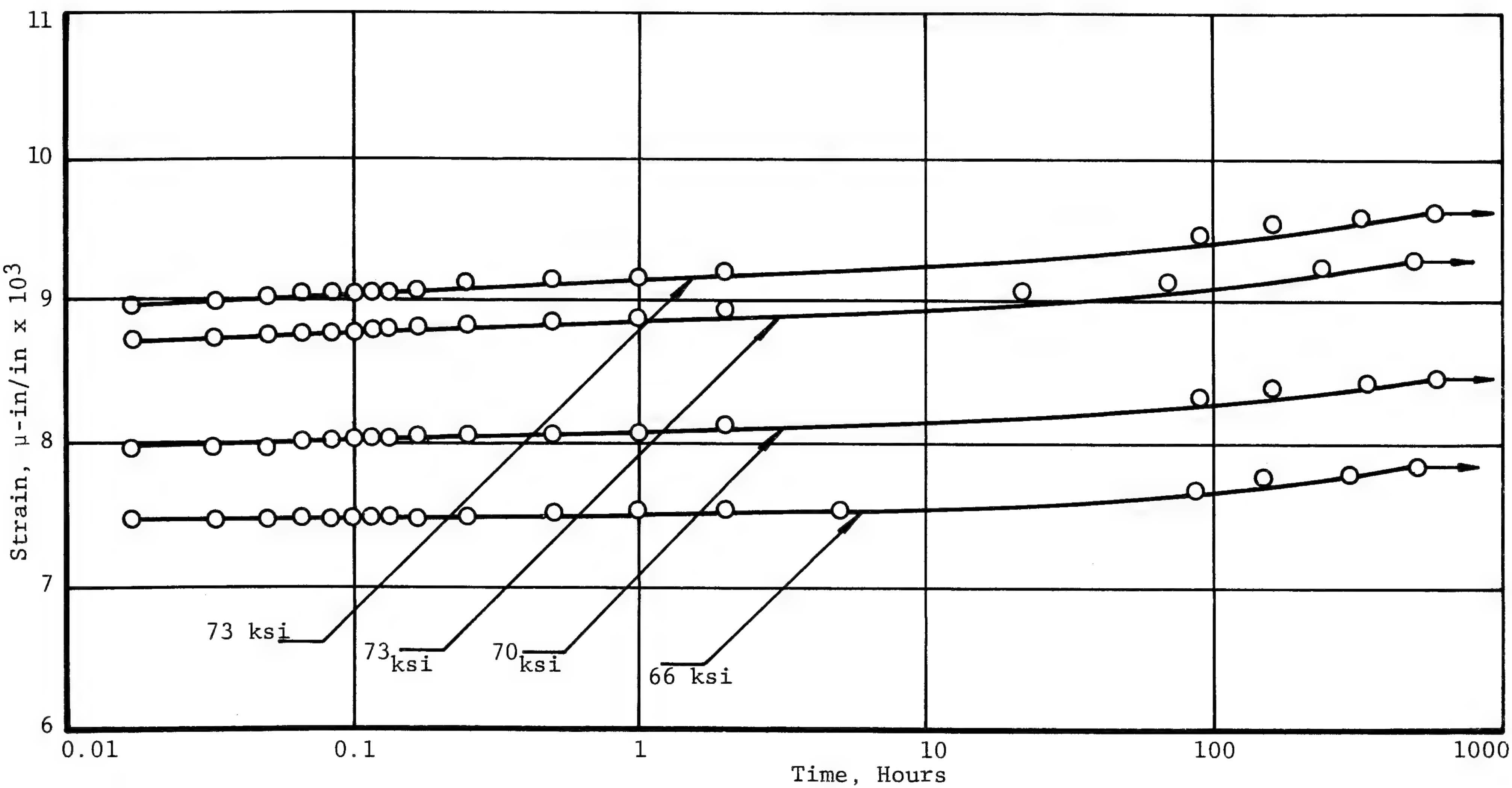


FIGURE 24 CREEP STRAIN VERSUS TIME CURVES FOR [$\pm$ 45L/OR/90R/90R/OR/OR/90R/90R/OR/$\mp$45L] T300 GRAPHITE/1014 S-GLASS/NARMCO 520$\overline{8}$ HYBRID COMPOSITES TESTED DRY AT T = 70°F.

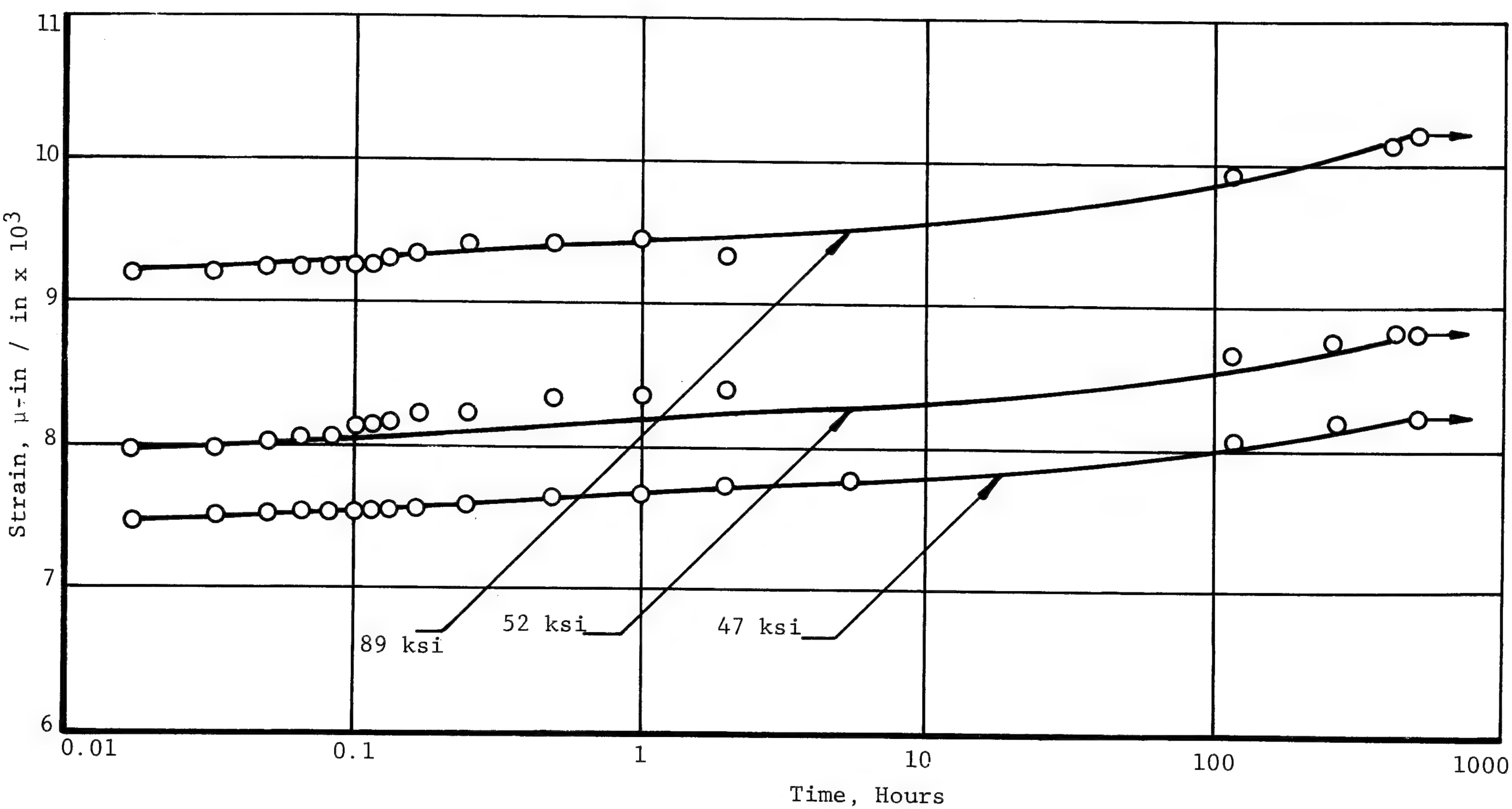


FIGURE 25 CREEP STRAIN VERSUS TIME CURVE FOR [∓45L/OR/90R/90L/OL/OL/90L/90R/OR/∓45L] T300 GRAPHITE/1014S-GLASS/NARMCO 5208 HYBRID COMPOSITES TESTED DRY AT T = 70°F

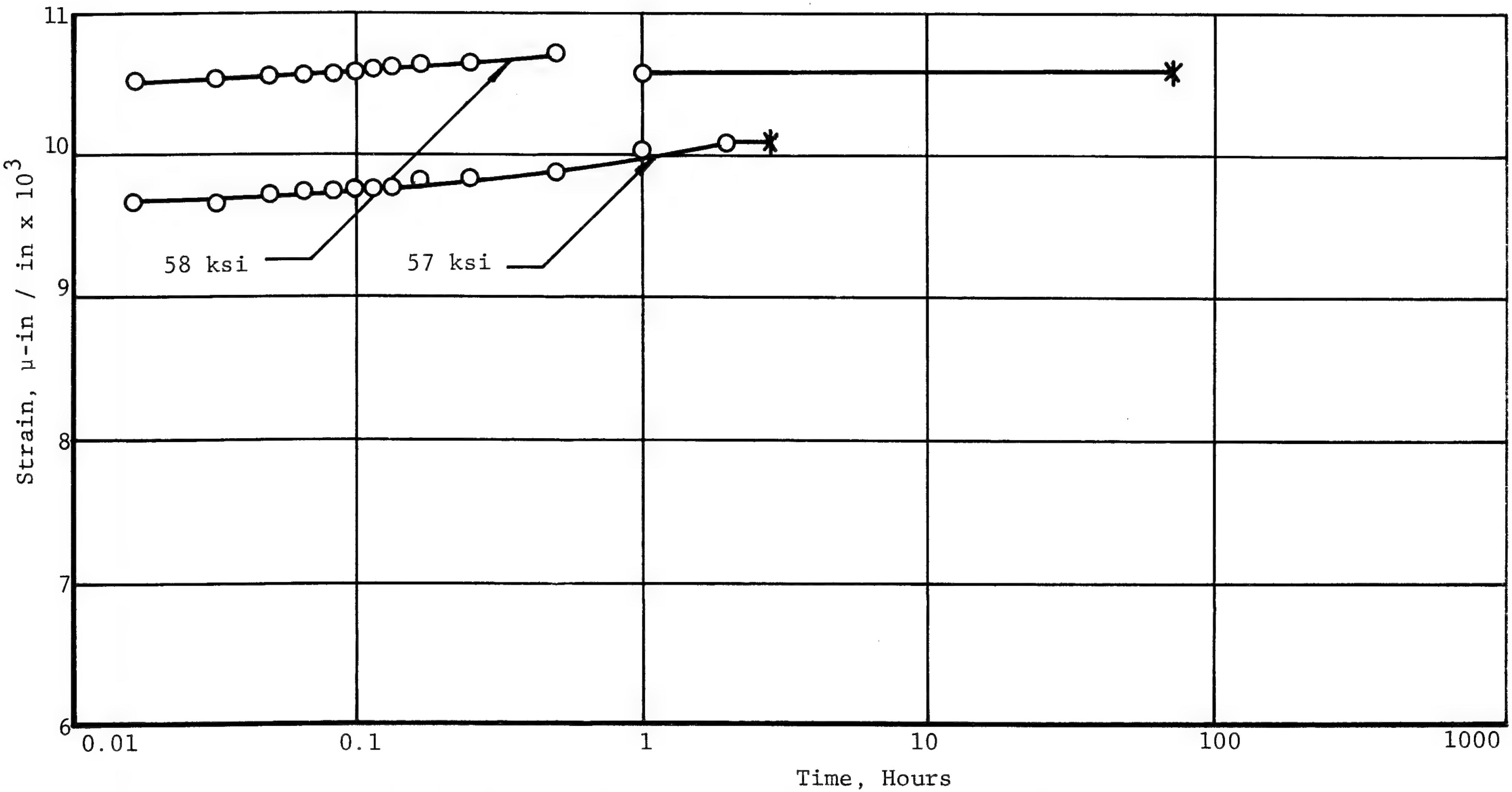


FIGURE 26 CREEP STRAIN VERSUS TIME CURVES FOR [∓45L/OR/90R/90L/OL/OL/90L/90R/OR/∓45L] T300 GRAPHITE/1014 S-GLASS/NARMCO 5208 HYBRID COMPOSITES TESTED DRY AT T = 70°F.

SECTION VI

6.0 SUMMARY AND CONCLUSIONS

The current study confirms previous work performed for NASC as described in reference 1. The following conclusions were reached on the basis of the results described herein.

- For a variety of stacking sequences, and under moisture saturated conditions, the elastic modulus of advanced composite hybrids (Graphite and S-Glass fibers) remains constant to the 10^7 cyclic level.

- The 67% glass (by plies) would appear to sacrifice very little fatigue resistance or creep strain over the 67% graphite (by plies) hybrids and the cost savings would be significant.

- The tensile fatigue resistance of glass/graphite/epoxy hybrids in the saturated (1%) condition appears to be greater than in the corresponding dry state.

- The phenomenom of increasing Poisson's ratio with stress-cycling of quasi-isotropic composites appears to be independant of stacking sequence.

- Principal failure modes for the 0° hybrids with graphite internal plies is by failure of the graphite first followed by load transfer to the glass. This is then followed

to gradual failure of the 0° glass plies. (As shown in the previous study, when the 0° graphite plies were on the outside, the initial failure of the graphite was almost immediately followed by failure of the internal 0° glass plies.

- For comparable stress levels the hybrid composite creep strains are quite low even when substantial glass content is present and in particular practical orientations such as quasi-isotropic, show little or no change in the amount of creep (over initial strain) for graphite to glass ratios of 67%, 50% or 33%. Thus creep would not pose a bigger problem as the glass content is increased. While the initial strain levels might be greater due to decreased modulus the proportionate creep remains about the same over the range of graphite to glass ratios studied.

RECOMMENDATIONS

Substantial cost reductions for advanced composite structures can be realized through hybridization. The effect on hybrid composites has been examined in the case of tension fatigue, tensile creep and impact. However certain other areas remain to be examined for the unidirectional and quasi-isotropic composites in order for their utilization to be generally accepted in the aerospace industry. These include:

- Effect of the combination of moisture and fully-reversed fatigue on the endurance of hybrids - The parameter which would certainly effect behavior most here would

be the influence of the material composition.

- Effect of small voids such as air entrapment in the resin on the moisture/fatigue resistance of hybrids.

- Creep resistance in compression of moisture laden hybrids.

- Effect of stress variation/moisture/voids combined on the fully-reversed fatigue behavior of hybrids. By appropriately stacking the hybrids and employing crack stoppers, the behavior would most certainly be enhanced.

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1. K. E. Hofer, Jr. and L. C. Bennett, "The Effects of Moisture on the Mechanical Performance of T300 Graphite Glass/Epoxy Hybrid Composites," Final Report NASC Contract No. N00019-75-C-0113, December, 1975.

2. N. Rao, and K. E. Hofer, "Fatigue Behavior of Graphite/ Glass/Epoxy Composites," Final Report IITRI Program D6070, April, 1973.

3. K. E. Hofer, Jr., et.al, "Development of Engineering Data on the Mechanical and Physical Properties of Advanced Composite Materials," AFML TR 74-266, February, 1975.

4. C. Browning, "The Effects of Moisture on the Properties of High Performance Structural Resins and Composites," AFML TR 72-94, September, 1972.

5. E. L. McKague, J. D. Reynolds, J. E. Halkias, "Life Assurance of Composite Structures," AFML TR 75-51, Volume I "Moisture Effects," May, 1975.

6. "Air Force Workshop on Durability Characteristics of Resin Matrix Composites at Battelle's Columbus Laboratories," September 30 and October 1-2, 1975.

7. G. S. Springer, and C. H. Shen, "Moisture Absorption in Graphite Epoxy Composites," AFML Contract F33615-75-C-5165.

8. Proceedings of "The Mechanics of Composites Review, Bergamo Center, Dayton, Ohio, January 28-29, 1976.

9. R. E. Trabacco and R. B. Pipes, "The Effect of Natural Aging and Weathering of Graphite/Epoxy Composites," presented at the "Program Review of Navy Sponsored Work on Composite Matierials," March 4-6, 1975.

10. K. E. Hofer, et.al, "Development of Engineering Data on the Mechanical and Physical Properties of Advanced Composite Materials," AFML, TR 72-205, Part I (September 1, 1972) and Part II (February, 1974).

11. I. M. Daniel, et. al, "Lamination Residual Stresses in Fiber Composites," Quarterly Progress Report No. 9, January, 1975.

12. I.M. Daniel, T. Liber, et. al, "Lamination Residual Stresses in Fiber Composites," Interim Report, NASA CR-134 826, IITRI D6073-I, March, 1975.

APPENDIX I

LAMINATE AND SPECIMEN FABRICATION DETAILS

APPENDIX I LAMINATE AND SPECIMEN FABRICATION DETAILS

This appendix describes the method by which the basic composite and hybrid composite materials were prepared for use on this program.

II.1 Material

Thornel 300 Graphite/Narmco 5208 is a current graphite/epoxy composite material which is being investigated widely for application to aerospace structural components. This material is available in a wide variety of forms but is generally utilized in the prepreg tape form.

The specification to which the Thornel 300 Graphite/Narmco 5208 material was ordered was:

General Dynamics specification: FMS 2023, Type III, Form A. "Graphite Fiber High Tensile Strength. Intermediate Modulus, Epoxy or Modified Epoxy Resin Impregnated," dated November 30, 1972 and all amendments.

This specification has been widely used throughout the industry and is available directly from General Dynamics Convair Division Fort Worth, Texas. The tape was in the 12-inch wide form.

The glass fiber/epoxy was the S-glass rovings/Narmco 5208 system. It was also utilized in the 12-inch wide prepreg tape form.

II.2 Material Procurement

Twenty lbs. of the graphite prepreg and five lbs. of the

glass prepreg were utilized during this program. The material was ordered in the 12" wide continuous tape form under the trade name Rigidite 5208/Thornel 300 Type III, Form A. After several batches of bad material of both fiber types had been rejected, batch No. 747 was delivered and accepted. The resin (solids) content, room temperature and 350°F flexural strengths and moduli and the horizontal shear strengths were determined for the 0° orientation by Whittaker Corporation Costa Mesa, California. The certification report by Whittaker that this batch conforms to Spec. FMS 2023 is presented in Tables IV and V.

Upon reciept of the materials from the prepregger, quality assurance panels were prepared. Longitudinal and transverse flex and 0° interlaminar shear specimens were cut from these panels and tested in accordance with recommended advanced composites test procedures. The results are shown in Table VI.

On the basis of these test results the materials were adjudged suitable for use on this program.

I.3 Laminate Fabrication

All lamina, laminates, hybrids and specimens were prepared at IITRI for use on this program.

The fabrication techniques followed at IITRI have been discussed in reference 1. An autoclave provided the pressure and temperature necessary to cure the Narmco 5208 epoxy in accordance with the following schedule recommended by General Dynamics for fabricating panels:

1. Full vacuum (26" HG) is applied to the bagged green layup.

TABLE IV

WHITAKER CORPORATION MATERIAL CERTIFICATION REPORT

NARMCO MATERIALS, INC.

A SUBSIDIARY OF CELANESE CORPORATION
600 VICTORIA STREET • COSTA MESA, CALIFORNIA 92627

CERTIFIED TEST REPORTS

SOLD TO: IIT Research Institute Purchasing Dept. 10 West 35th Street Chicago, Illinois 60616	COSTA MESA 714/548-1144 TWX 910-596-1375	NO. 66- 32067 A	INVOICE NUMBER
		DATE 12/7/76	PAGE 1 OF 1
		CUST. ORDER NO. J. Anderson 46567	DATE 10/12/76

TESTING RESULTS

ITEM #1
MATERIAL Rigidite 5208-S1014-12"
Batch #800

Roll	Amount	Resin Content	Areal Fiber Weight	Mfg.Date	Test Date
2	14.6 lbs	32%	205 gm/sq.m^2	12/7/76	12/7/76

Warranty expires: 3/7/77 @ 40°F.

This is to certify that the above material was manufactured, tested and found to conform to the applicable specification and terms of the purchase agreement, as indicated by the above test results.

Jack W. Mansfield
Quality Control Representative

TO THE BEST OF OUR KNOWLEDGE THE INFORMATION CONTAINED HEREIN IS ACCURATE. HOWEVER, NEITHER CELANESE CORPORATION NOR ANY OF ITS AFFILIATES ASSUMES ANY LIABILITY WHATSOEVER FOR THE ACCURACY OR COMPLETENESS OF THE INFORMATION CONTAINED HEREIN. FINAL DETERMINATION OF THE SUITABILITY OF ANY INFORMATION OR MATERIAL FOR THE USE CONTEMPLATED, THE MANNER OF USE AND WHETHER THERE IS ANY INFRINGEMENT OF PATENTS IS THE SOLE RESPONSIBILITY OF THE USER.

TABLE V

NARMCO MATERIALS, INC.

A SUBSIDIARY OF CELANESE CORPORATION
600 VICTORIA STREET • COSTA MESA, CALIFORNIA 92627

CERTIFIED TEST REPORTS

SOLD TO
IIT Research Institute
Purchasing Dept.
10 West 35th Street
Chicago, Illinois 60616

COSTA MESA
714/548-1144
TWX
910-596-1375

NO. 66- 32067	INVOICE NUMBER
DATE 7-26-76	PAGE 1 OF 1
CUST. ORDER NO. 46567 J. Anderson	DATE 5-13-76 Chg.#1 (7-23-76)

TESTING RESULTS

ITEM #3
MATERIAL Rigidite 5208-T300 (12")
Batch #747

Roll:	13
Amount:	25.7 lbs.
Resin Content:	42%
Fiber Weight:	155 grams/m^2
Volatiles:	0.4%
Mfg. Date:	7-22-76
Test Date:	7-22-76

RECEIVED
JUL 27 1976
IITRI

Warranty expires: 10-26-76 @ 0°F.

This is to certify that the above material was manufactured, tested and found to conform to the applicable specification, and terms of the purchase agreement, as indicated by the above test results.

Quality Control Representative

TABLE VI

IITRI QUALITY ASSURANCE MECHANICAL PROPERTY TEST RESULTS FOR T-300 GRAPHITE/NARMCO 5208 AND S-GLASS ROVINGS/NARMCO 5208 PREPREG MATERIALS

T-300 GRAPHITE/NARMCO 5208

0° Flex strength (ksi)	:	267
90° Flex strength (ksi)	:	8.5
Interlaminar Shear strength (ksi)	:	14.7

S-GLASS/NARMCO 5208 (Batch 3)

0° Flex strength (ksi)	:	237
90° Flex strength (ksi)	:	11.5
Interlaminar Shear strength (ksi)	:	11.1

2. The panel is heated from room temperature to 275°F + 5°, -10°F in 40 ± 8 minutes (corresponding to a 4 to 6 degrees F/minute heat up rate).

3. The layup is held at full vacuum and 275°F + 5°F -10°F for 60 ± 5 minutes.

4. Pressure is then increased to 80 psi ± 5 psi. The vacuum is vented to outside air when the pressure has reached 25 psi.

5. Upon reaching 85 ± 5 psi, the temperature is increased to 355°F ± 10°F - 5°F in 15 ± 3 minutes.

6. The system is held at 85 psi ± 5 psi and 355°F + 10°F -5°F for 120 ± 5 minutes.

7. The system is then cooled to 140°F maintaining the 85 psi ± 5 psi pressure in not less than 30 minutes.

8. The panels are postcured subsequently for 240 ± 5 minutes at 400°F ± 10°F. The heatup rate for postcuring panels is from RT to 400°F in 64 ± 10 minutes.

Throughout the postcure, the panels are loosely supported between two layers of 1/2 to 3/4 inch thick aluminum honeycomb core.

The quality assurance panel layups consisted of 15 and 18 plies covered with 1 ply of 1581 bleeder cloth and 1 ply of 181 vent cloth. Fiber volumes of approximately 4% were obtained using a top surface caul plate.

All laminates were examined using ultrasonic C-scan NDT procedures. The orientations and ply arrangements for the various laminates were discussed in the body of the report. To assist in this effort an N.D.T test panel, with voids purposelully placed on the inside of the panel was prepared. The panel was an eight ply [0°/90°/0°/0°/0°/0°/90°/0°] with the flaws between the middle two zero degree plies. The panel measured 6" x 14" and contained 1) a piece of masking tape, 2) a strip of polyethylene film, 3) a strip of teflon vent film 4) a section of release paper. One-twenty cloth was added to the laminate in the areas not occupied by the various flaws so as to maintain continuity of thickness over the panel area. This panel was used to establish the gate for the C-scan for acceptance or rejection of all test panels.

I.4 Specimen Fabrication Procedures

This section briefly lists the test specimens and procedures utilized for generating the data during this program. A detailed description of the test specimens, specimen fabrication procedures and test equipment is found in Reference 10.

The same specimen configuration was utilized for tension fatigue (R = 0.1) and creep tests. The IITRI straight-sided tab ended coupon was utilized for these properties. After environmental conditioning and/or fatigue cycling each static tensile specimen was fitted with three electrical-resistance foil strain gages.

The specimens used for all flexural testing was the fifteen ply, coupon universally used for testing advanced compos tes. Specimens were loaded in a 3 (0° coupon) or 4-point (90° coupons) bending fixture. Elevated temperature tests were conducted in a Missimer circulating air oven and loads were applied in tension to a flexural test rig.

The interlaminar shear strength of oriented fiber composites was determined on short beam shear specimens. Elevated temperature tests were performed with the assistance of the fixture described above.

The principal* mechanical properties for the S-Glass/Narmco 5208, the T-300 Graphite/Narmco 5208 and the S-Glass/T-300 Graphite/Narmco 5208 Hybrid composites are shown in Table VII. They are used frequently as the reference baseline data in the subsequent fatigue, residual strength and creep studies. These properties are well characterized and were taken from the literature in an effort to concentrate more thoroughly on the major objectives of this current program.

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* The principal mechanical properties include those properties of the basic lamina parallel to and transverse to the fiber direction.

TABLE VII PRINCIPAL PROPERTIES OF T-300 GRAPHITE AND S-GLASS REINFORCED NARMCO 5208 EPOXY COMPOSITES

Material/ Orientation	Property	Temp. (°F)	Strength (ksi)	Elastic Modules (msi)	Poisson's Ratio (in/in)	Reference *
T-300/0°	Tension	70°F 260°F 350°F	218 214 208	26.3 29.8 28.5	0.28 0.31 0.26	Ref. 3 Ref. 3 Ref. 3
	Compression	70°F 260°F 350°F	218 208 206	23.0 21.7 22.5	0.34 0.30 0.31	Ref. 3 Ref. 3 Ref. 3
T-300/90°	Tension	70°F 260°F 350°F	5.85 4.11 2.89	1.50 1.68 1.78	0.01 0.01 0.01	Ref. 3 Ref. 3 Ref. 3
	Compression	70°F	36.3 32.6 30.4	1.64 1.68 1.60	0.01 0.01 0.01	Ref. 3 Ref. 3 Ref. 3
S-Glass/0°	Tension	70°F	260	8.8	0.23	Ref. 11
	Compression	70°F	119	--	--	Ref. 12
S-Glass/90°	Tension	70°F	6.7	3.6	0.09	Ref. 12
	Compression	70°F	25.3	--	--	Ref. 12

* See References at end of Report.

APPENDIX II

INDIVIDUAL FATIGUE TEST
RESULTS
AND S-N CURVES

Appendix II INDIVIDUAL FATIGUE TEST RESULTS AND S-N CURVES

This appendix presents the data for the basic and hybrid composites. It is restricted to the basic S-N curves and individual fatigue coupon cycle information. The next appendix presents the results of the individual specimen utilized in the residual strength and residual mechanical properties test determinations.

Table VIII shows the individual specimen by specimen test results. It includes specimen thickness on a ply basis fiber orientation, prior conditioning, cyclic stress level and cycles to failure or at runout and the residual strength of all runouts as appropriate. Figures 27 through 38 present the maximum tensile stress per cycle versus cycles to failure curves for all materials as they were generated on this program.

TABLE VIII TENSILE FATIGUE TEST UNITS FOR VARIOUS HYBRID COMPOSITES (T300 GRAPHITE/1014 S-GLASS/NARMCO 5208 EPOXY) TESTED AT T = 75°F WITH AND WITHOUT EXPOSURE TO A VARIETY OF PRECONDITIONING TREATMENTS (R = 0.1, ϕ = 1800 cpm)

Specimen No.	Material and Orientation	Prior Conditioning	Stress Level (ksi)	Cycles to Failure (Cycles)	Residual Strength (ksi)	Comments
1	[OL/OR/OL/O_2R/OL/OR/OL]	Dry	150	2,000	-	
2			140	2,000	-	
3			130	6,000	-	
4			120	194,000	-	
5			125	5,000	-	
6			115	884,000	-	
7			140	10,000	-	
8			125	122,000	-	
9			130	94,000	-	
10			115	31,000		
21			120	691,000	-	
22			140	2,000	-	
23			125	846,000	-	
24			150	3,000	-	
25			130	21,000	-	

TABLE VIII TENSILE FATIGUE TEST RESULTS OF VARIOUS HYBRID COMPOSITES (T = 300 GRAPHITE/1014 S-GLASS/NARMCO 5208 EPOXY) TESTED AT T = 75°F WITH AND WITHOUT EXPOSURE TO A VARIETY OF PRECONDITIONING TREATMENTS (R = 0.1, ϕ = 1800 cpm).

Specimen No.	Material And Orientation	Prior Conditioning	Stress Level (ksi)	Cycles to Failure (cycles)	Residual Strength (ksi)	Comments
2:1-8	$[0_2L/0_4R/0_2L]$	dry	135	127,000		
9			140	29,000		
10			145	14,000		
26			150	16,000		
27			148	17,000		
28			130	559,000		
29			145	20,000		
30			126	158,000		
41			160	1,000		
42			155	8,000		
43			135	33,000		
44			140	51,000		
45			160	17,000		
46			155	2,000		
47			130	7,000		
48			126	197,000		
49			120	489,000		
50			130	693,000		
51			160	2,000		
52			120	2,231,000		
2			110	2,002,000*		
3			115	2,300,000*		
4			118	1,166,000		
6			123	758,000		
7			130	95,000		

*No Failure

TABLE VIII TENSILE FATIGUE TEST RESULTS FOR VARIOUS HYBRID COMPOSITES (T300 GRAPHITE/1014 S-GLASS/NARMCO 5208 EPOXY) TESTED AT T = 75° WITH AND WITHOUT EXPOSURE TO A VARIETY OF PRECONDITIONING TREATMENTS ($R = 0.1$, $\phi = 1800$ cpm)

Specimen No.	Material and Orientation	Prior Conditioning	Stress Level (ksi)	Cycles to Failure (Cylces)	Residual Strength (ksi)	Comments
1:2-1	[$\pm$45L/OR/90R/90L/0_2L/ 90L/90R/OR/$\mp$45L]	dry	45	126,000	-	-
2			50	4,000	-	Tab Area Failure
3			42	497,000	-	"
4			50	70,000	-	-
5			42	195,000	-	Tab Area Failure
6			45	128,000	-	"
7			47	100,000	-	-
8			47	2,000	-	-
9			40	456,000	-	-
10			48	114,000	-	-
1A			Static Strength = 62.7 ksi			

TABLE VIII TENSILE FATIGUE TEST RESULTS OF VARIOUS HYBRID COMPOSITES (T = 300 GRAPHITE/1014 S-GLASS/NARMCO 5208 EPOXY) TESTED AT T = 75°F WITH AND WITHOUT EXPOSURE TO A VARIETY OF PRECONDITIONING TREATMENTS (R = 0.1, ϕ = 1800 cpm).

Specimen No.	Material And Orientation	Prior Conditioning	Stress Level (ksi)	Cycles to Failure (cycles)	Residual Strength (ksi)	Comments
1:1 - 26	[OL/OR/OL/O_2R/OL/OR/OL]	Wet	100	2,051,000*	147.4	Tab Failure
1:1 - 27			115	62,000	-----	----------
1:1 - 28			120	3,000	-----	----------
1:1 - 29			113	1,264,000	-----	----------
1:1 - 30			110	2,270,000*	157.4	----------
2:1 - 16	[OL/O_4R/OL]	Wet	100	165,000	-----	----------
2:1 - 17			105	3,315,000*	152.3	----------
2:1 - 18			120	5,165,000*	173.3	Tab Failure
2:1 - 19			140	976,000	-----	----------
2:1 - 20			155	10,000	-----	----------
1:2 - 31	[O_2L/O_2R/O_2L]	Wet	100	2,982,000*	122.8	Tab Area Failure
1:2 - 32			120	284,000	-----	----------
1:2 - 35			130	10,000	-----	---------
1:2 - 37			125	256,000	-----	---------
1:2 - 38			118	624,000	-----	---------
1:2 - 40			128	856,000	-----	---------

* No Failure

TABLE VIII TENSILE FATIGUE TEST RESULTS FOR VARIOUS HYBRID COMPOSITES (T300 GRAPHITE/1014 S-GLASS/NARMCO 5208 EPOXY) TESTED AT T = 75°F WITH AND WITHOUT EXPOSURE TO A VARIETY OF PRECONDITIONING TREATMENTS (R = 0.1, ϕ = 1800 cpm)

Specimen No.	Material and Orientation	Prior Conditioning	Stress Level (ksi)	Cycles to Failure (Cycles)	Residual Strength (ksi)	Comments
1:1-1	[$\pm$45L/OR/90_2R/OR/$\mp$45L]	dry	50	2,673,000	-	delam at startup
2			65	1,000	-	"
3			60	2,000	-	"
4			55	6,000	-	"
5			55	300,000	-	"
6			60	1,000	-	"
7			57.5	7,000	-	"
8			56.5	2,000	-	"
9			52	4,097,000	-	"
10			50	5,000,000*	67.2	"
11			Static Strength = 77.2 ksi			

*No Failure

TABLE VIII TENSILE FATIGUE TEST RESULTS OF VARIOUS HYBRID COMPOSITES (T = 300 GRAPHITE/1014 S-GLASS/NARMCO 5208 EPOXY) TESTED AT T = 75°F WITH AND WITHOUT EXPOSURE TO A VARIETY OF PRECONDITIONING TREATMENTS (R = 0.1, ϕ = 1800 cpm).

Specimen No.	Material And Orientation	Prior Conditioning	Stress Level (ksi)	Cycles to Failure (cycles)	Residual Strength (ksi)	Comments
2:1-1	[$\pm$45L/0R/90_2R/0_2R/90_2R/0R/$\mp$45L]	dry	65	603,000	-	Large deformation under static load
2			70	221,000	-	"
3			75	2,000	-	"
4			75	2,000	-	"
5			73	27,000	-	"
6			73	10,000	-	"
7			63	107,000	-	"
8			65	2,680,000*	77.5	"
9			70	5,000	-	"
10			63	2,450,000*	73.4	"
21			70	28,000	-	Tab area failure
22			63	560,000	-	-
23			67	3,000	-	-
24			65	6,000	-	-
25			Static Strength = 87.7 ksi		-	-

*No Failure

TABLE VIII TENSILE FATIGUE TEST RESULTS OF VARIOUS HYBRID COMPOSITES (T = 300 GRAPHITE/1014 S-GLASS/NARMCO 5208 EPOXY) TESTED AT T = 75°F WITH AND WITHOUT EXPOSURE TO A VARIETY OF PRECONDITIONING TREATMENTS (R = 0.1, ϕ = 1800 cpm).

Specimen No.	Material And Orientation	Prior Conditioning	Stress Level (ksi)	Cycles to Failure (cycles)	Residual Strength (ksi)	Comments
1:2-1	[$0_2L/0_2R/0_2L$]	Dry	110	12,000	-	
2			120	15,000	-	
3			100	157,000	-	
4			90	692,000	-	
5			130	2,000	-	
6			110	66,000	-	
7			120	39,000	-	
8			100	312,000	-	
9			90	351,000	-	
10			130	1,000	-	
16			85	1,285,000	-	
17			85	1,391,000	-	
18			125	7,000	-	
19			125	6,000	-	
20			110	109,000	-	

*No Failure

TABLE VIII TENSILE FATIGUE TEST RESULTS OF VARIOUS HYBRID COMPOSITES (T = 300 GRAPHITE/1014 S-GLASS/NARMCO 5208 EPOXY) TESTED AT T = 75°F WITH AND WITHOUT EXPOSURE TO A VARIETY OF PRECONDITIONING TREATMENTS (R = 0.1, ϕ = 1800 cpm).

Specimen No.	Material And Orientation	Prior Conditioning	Stress Level (ksi)	Cycles to Failure (cycles)	Residual Strength (ksi)	Comments
1:1-11	[$\pm$45°L/OR/90_2R/OR/$\mp$45L]	Wet	55	160,000	-	Resin appears soft
12			65	2,000	-	Early delamination
13			50	5,110,000*	60.7	"
14			62	14,000	-	"
15			57	13,000	-	"
2:1-11	[$\pm$45L/OR/90_2R/0_2R/90_2R/OR/$\mp$45L]	Wet	40.2	2,440,000*	85.3	
12			46.4	2,340,000*	87.6	
13			59.4	2,570,000*	88.2	
14			52.6	2,740,000*	85.8	
15			65	3,000,000*	84.3	
1:2-11	[$\pm$45L/OR/90R/90L/0_2L/90L/90R/OR/$\mp$45L]	Wet	45	1,002,000	-	
12			50	110,000	-	
13			55	8,000	-	
14			53	100,000	-	
15			48	921,000	-	

*No Failure

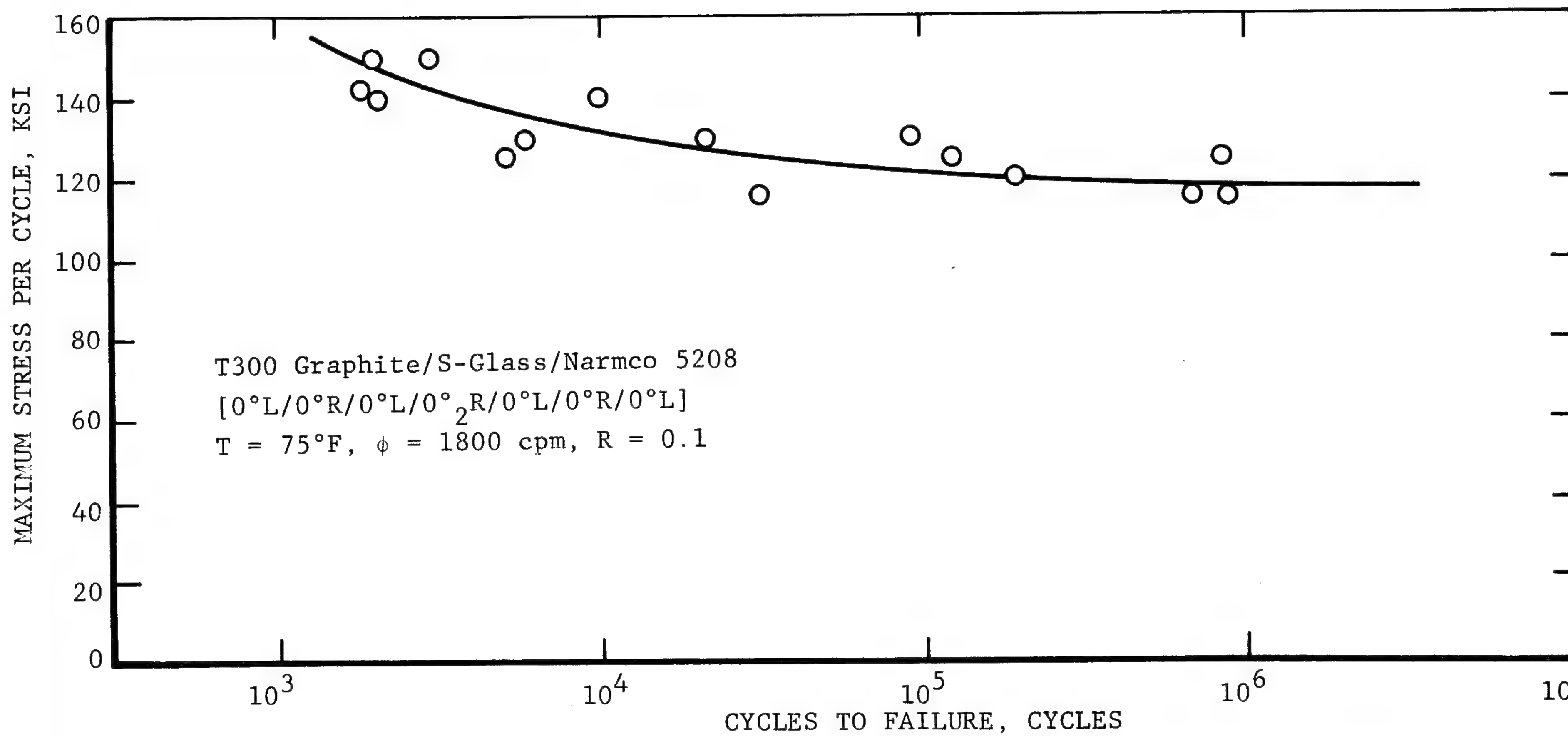

Figure 27 Fatigue S-N Curve for T300/S-Glass/Narmco 5208 Hybrid Composite Tested in Air (Tension-Tension)

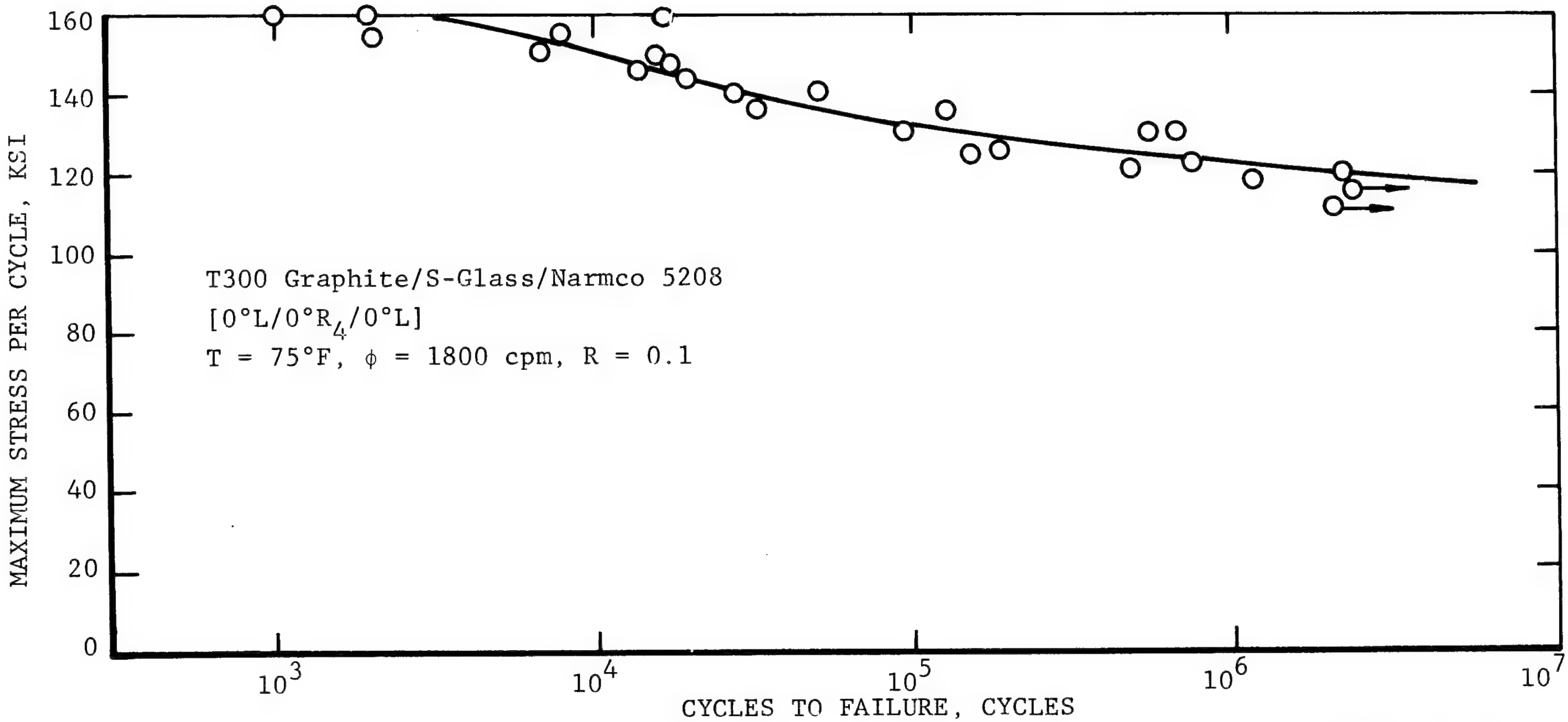

Figure 28 Fatigue S-N Curve for T-300/S-Glass/Narmco 5208 Hybrid Composite Tested in Air (Tension-Tension)

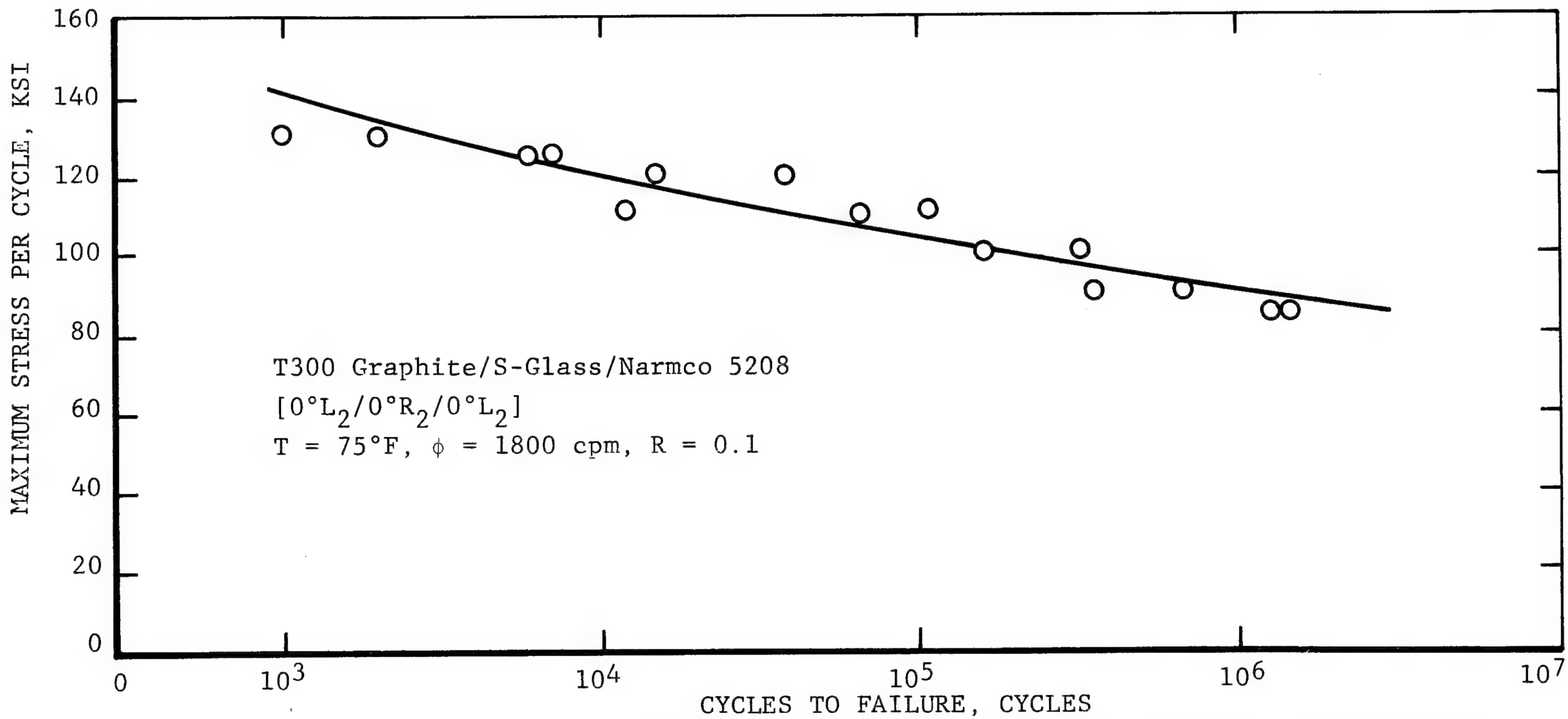

Figure 29 Fatigue S-N Curve for T300/S-Glass/Narmco 5208 Hybrid Composite Tested in Air (Tension-Tension)

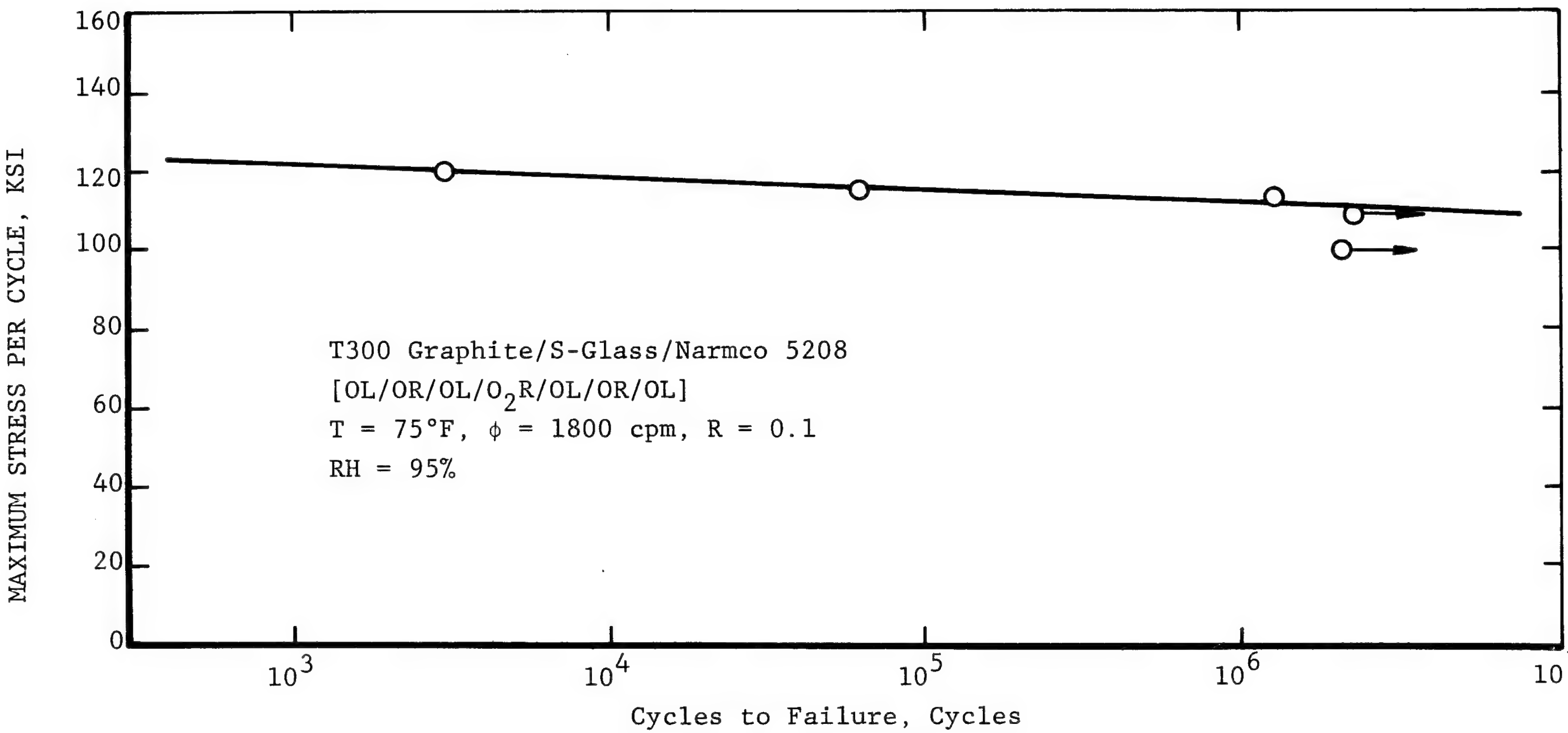

FIGURE 30 FATIGUE S-N CURVE FOR T300/S-GLASS/NARMCO 5208 HYBRID COMPOSITE TESTED WET (Tension-Tension) AFTER EXPOSURE TO 98% RH/165°F FOR 300 HOURS.

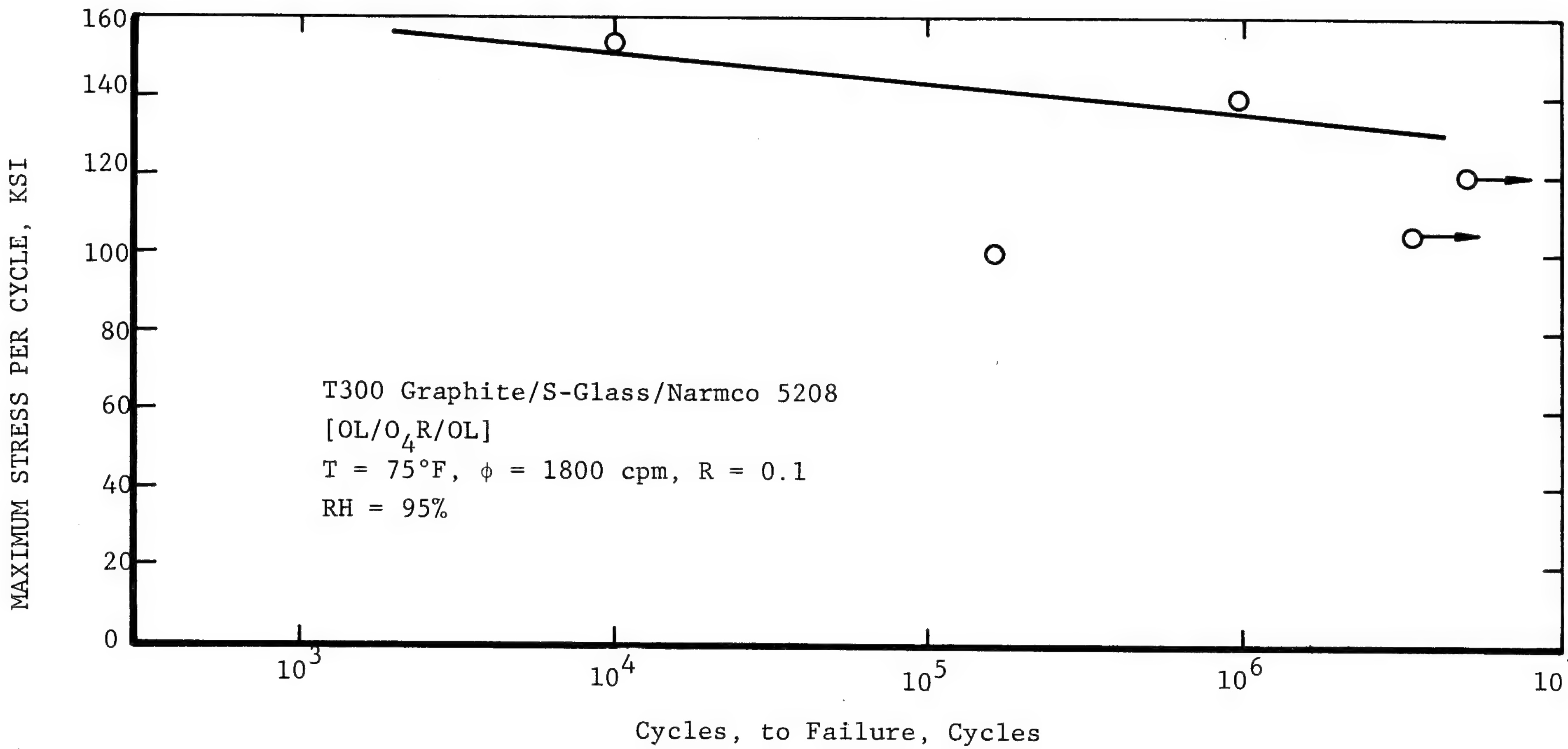

FIGURE 31 FATIGUE S-N CURVE FOR T300/S-GLASS/NARMCO 5208 HYBRID COMPOSITE TESTED WET (Tension-Tension) AFTER EXPOSURE TO 98% RH/165°F FOR 300 HOURS.

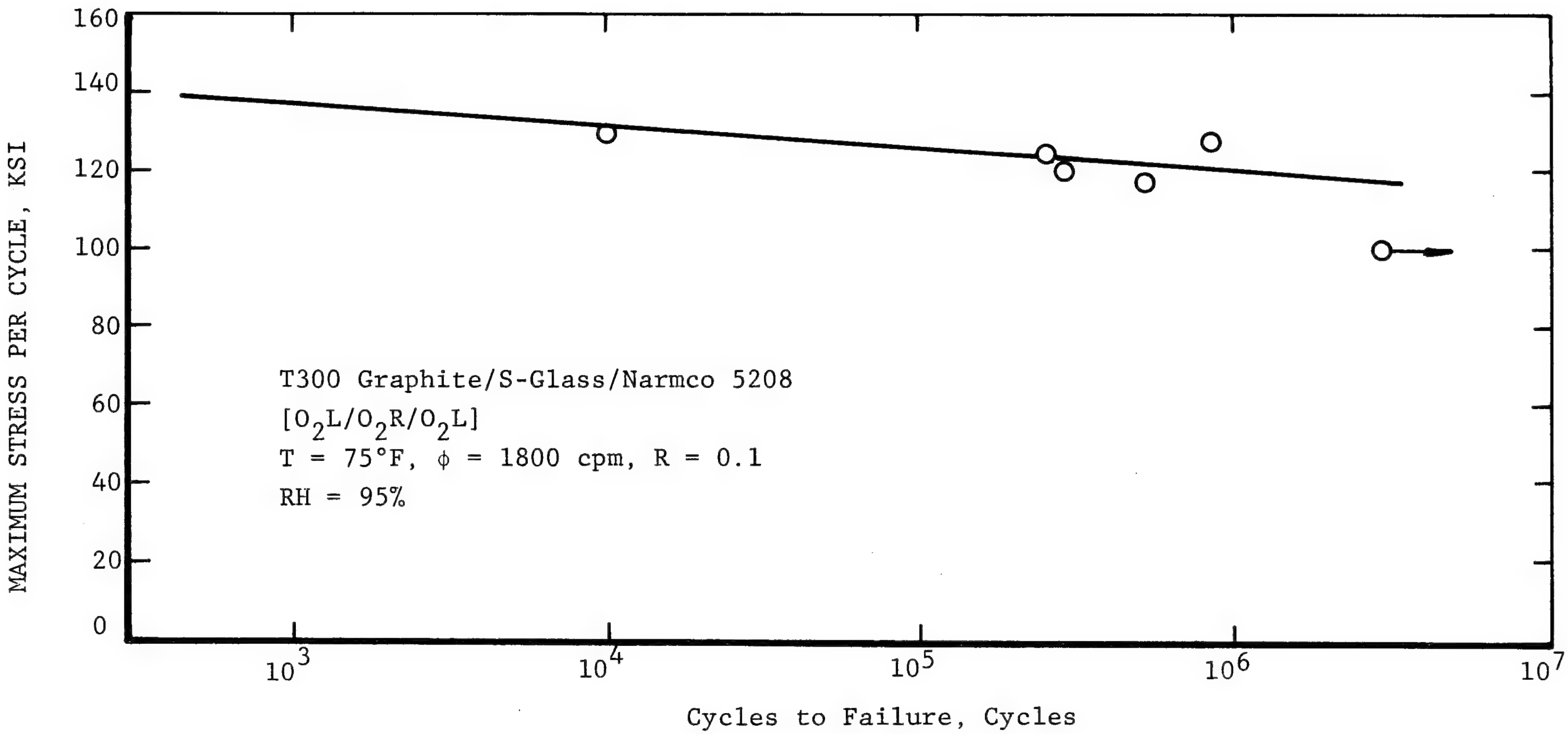

FIGURE 32 FATIGUE S-N CURVE FOR T300/S-GLASS/NARMCO 5208 HYBRID COMPOSITE TESTED WET (Tension-Tension) AFTER EXPOSURE TO 98% RH/165°F FOR 300 HOURS.

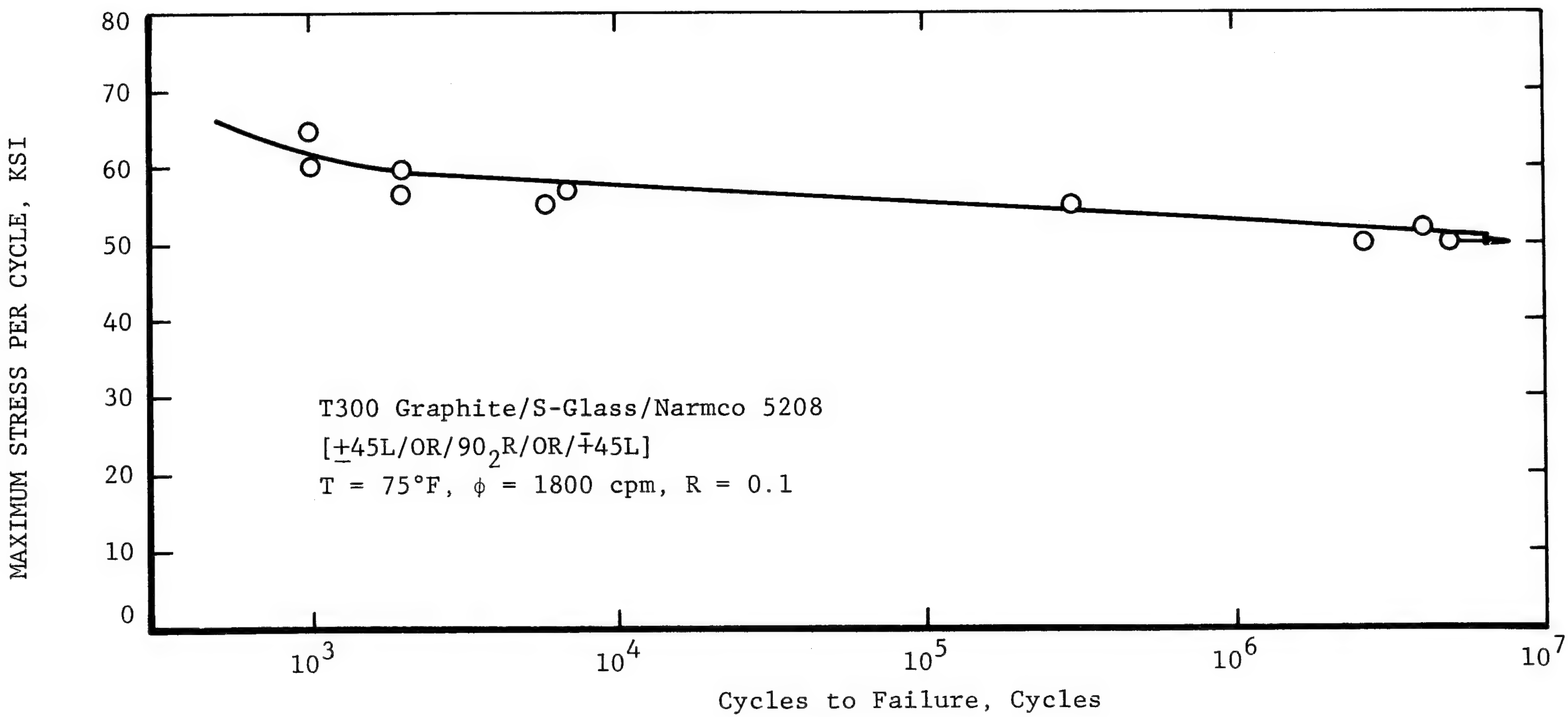

FIGURE 33 FATIGUE S-N CURVE FOR QUASI-ISOTROPIC T300/S-GLASS/NARMCO 5208 HYBRID COMPOSITE TESTED IN AIR (Tension-Tension).

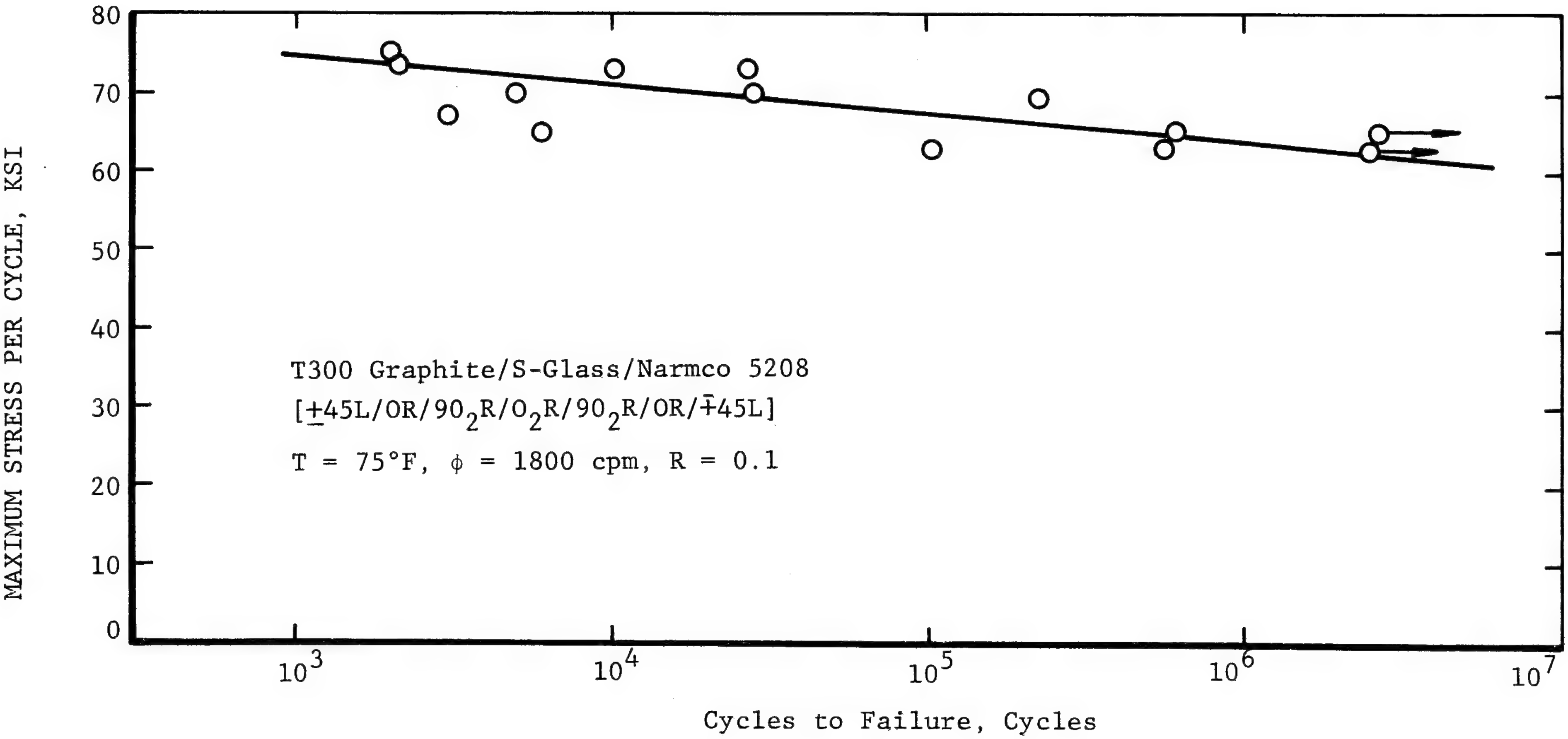

FIGURE 34 FATIGUE S-N CURVE FOR QUASI-ISOTROPIC T300/S-GLASS/NARMCO 5208 HYBRID COMPOSITE TESTED IN AIR (Tension-Tension).

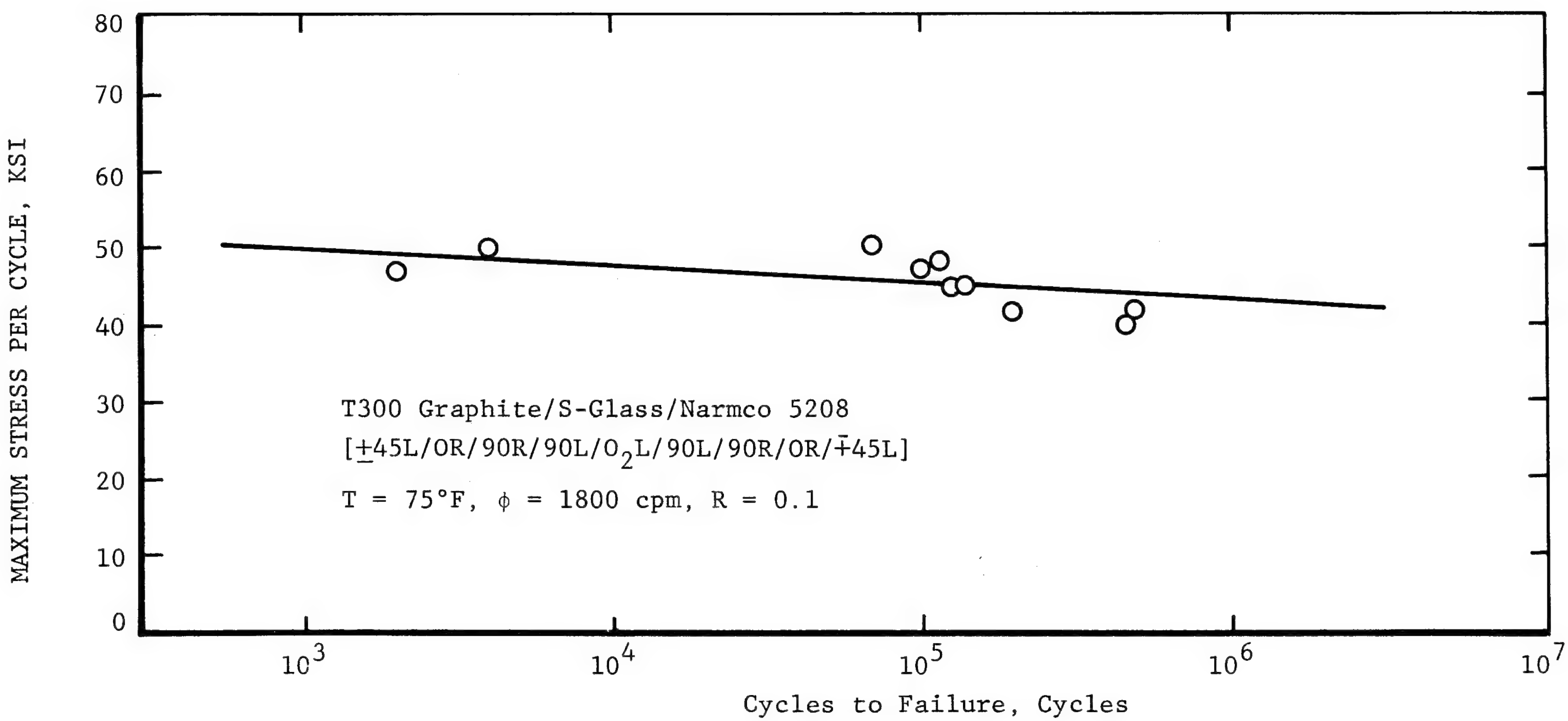

FIGURE 35 FATIGUE S-N CURVE FOR QUASI-ISOTROPIC T300/S-GLASS/NARMCO 5208 HYBRID COMPOSITE TESTED IN AIR (Tension-Tension).

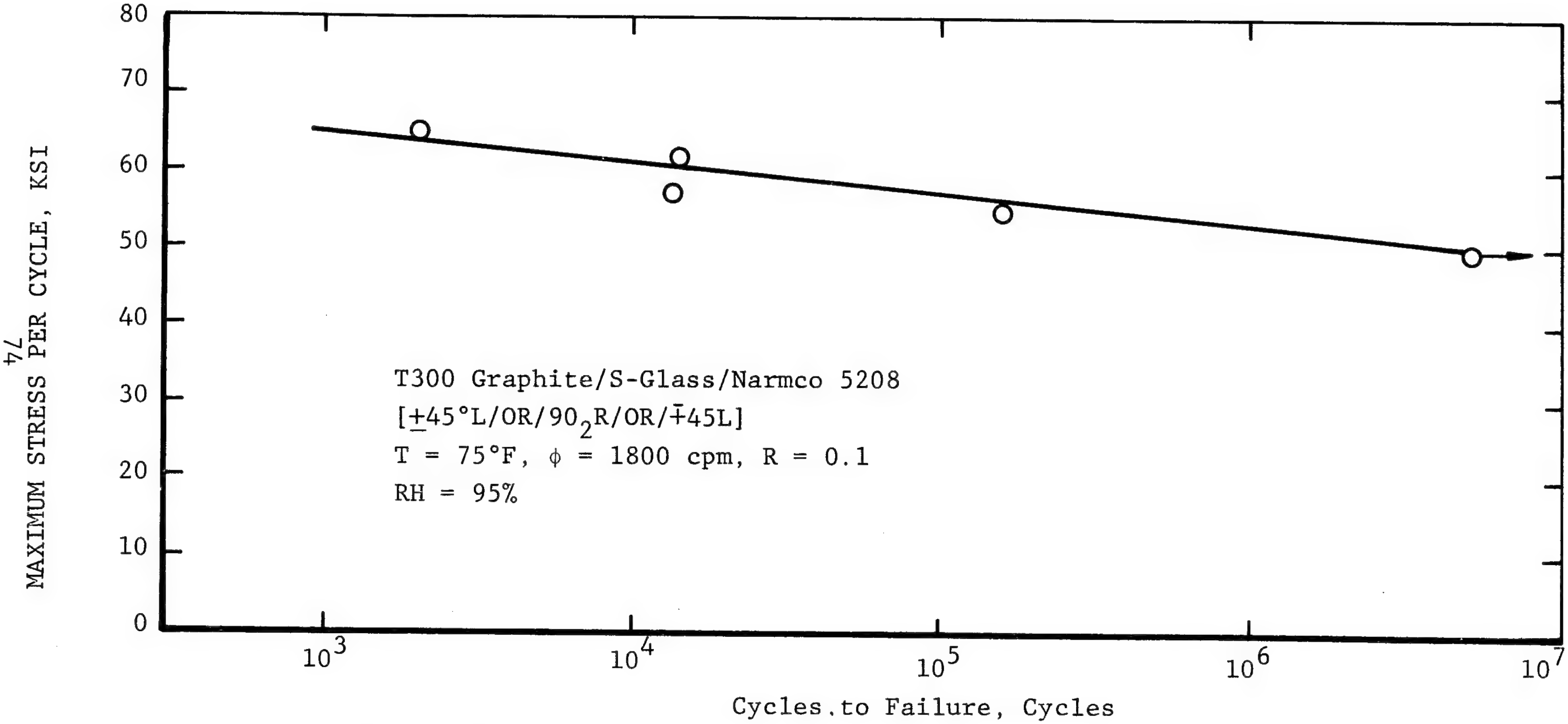

FIGURE 36 FATIGUE S-N CURVE FOR QUASI-ISOTROPIC T300/S-GLASS/NARMCO 5208 HYBRID COMPOSITES TESTED WET (Tension-Tension) AFTER EXPOSURE TO 98% RH/165°F FOR 300 HOURS.

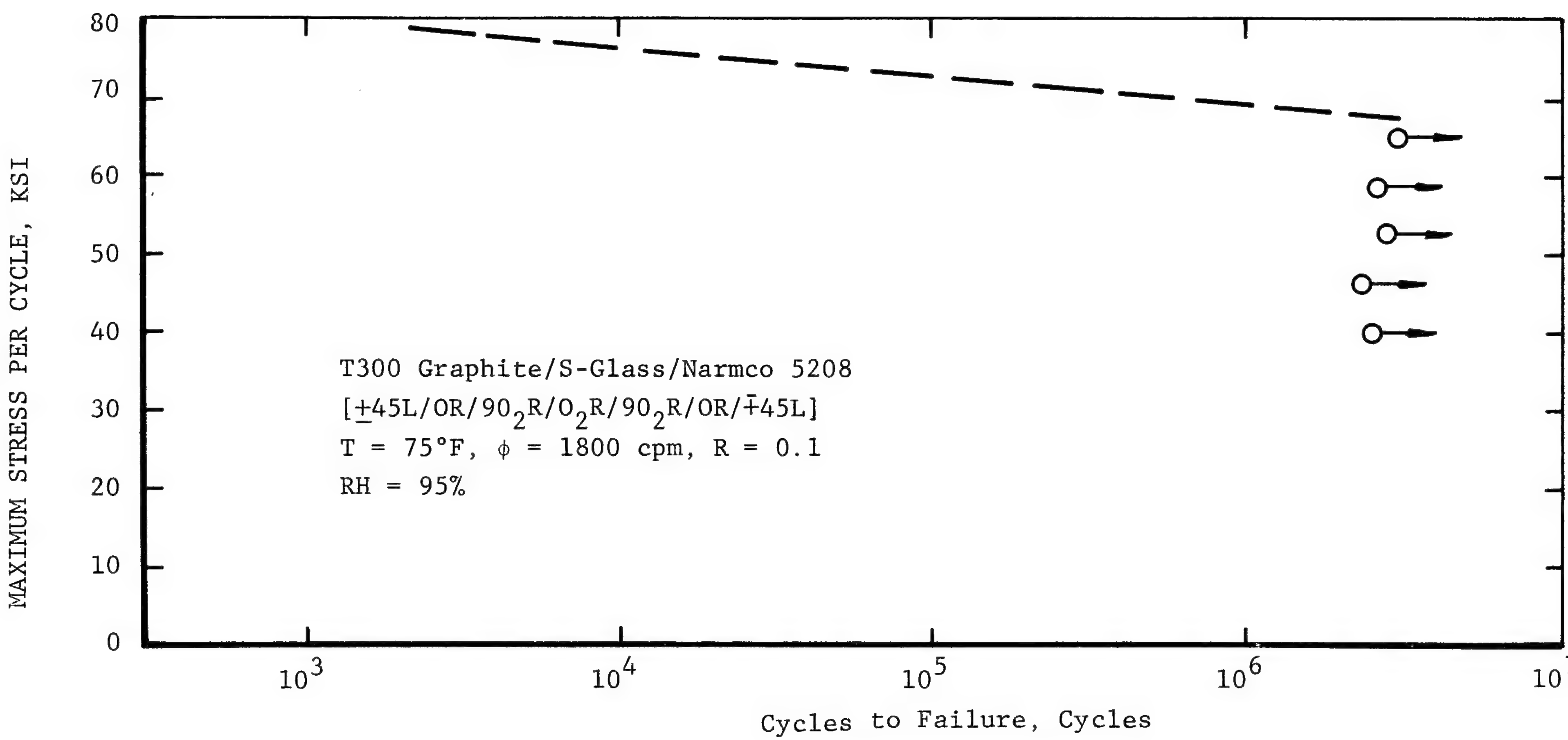

FIGURE 37 FATIGUE S-N CURVE FOR QUASI-ISOTROPIC T300/S-GLASS/NARMCO 5208 HYBRID COMPOSITE TESTED WET AFTER EXPOSURE TO 98% RH/165°F FOR 300 HOURS.

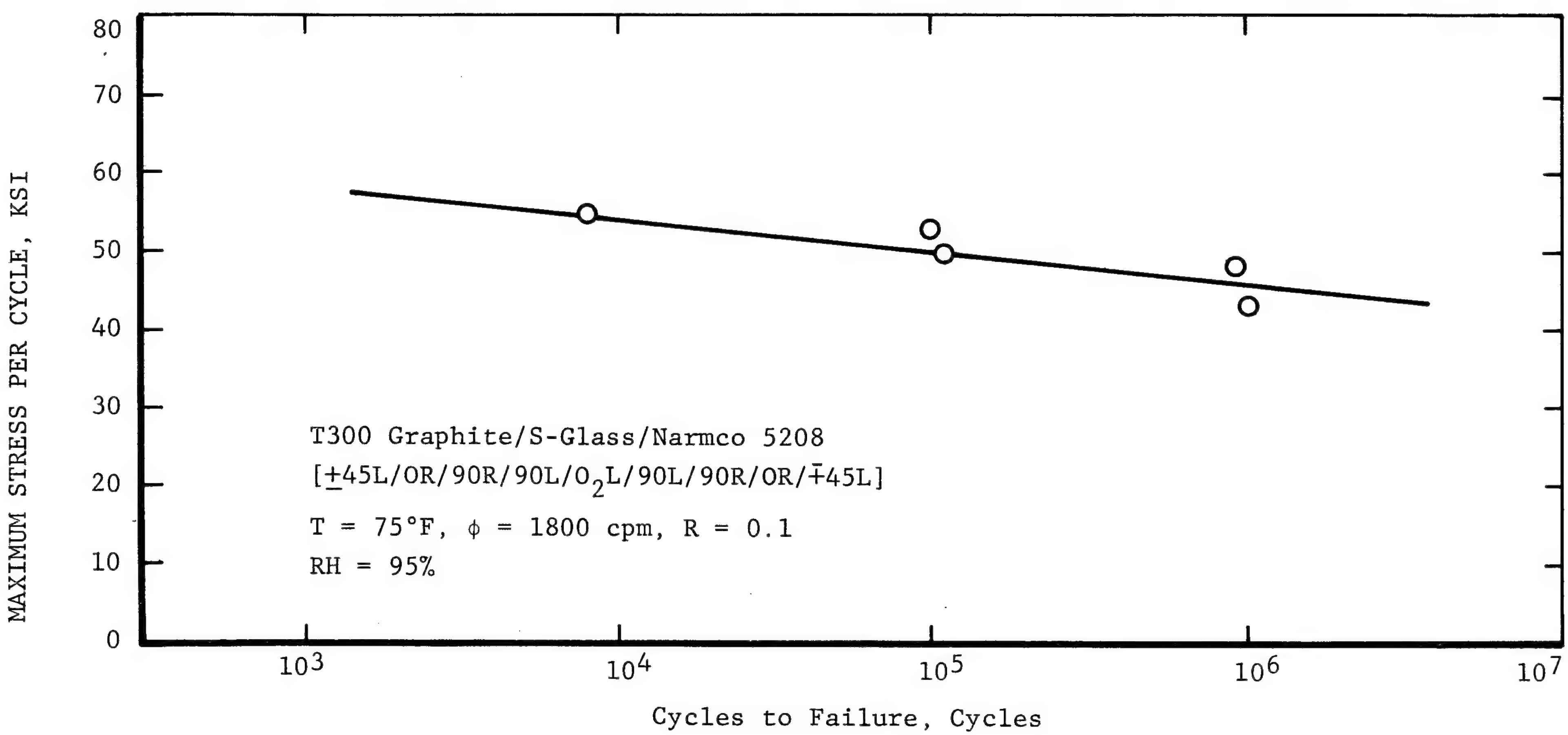

FIGURE 38 FATIGUE S-N CURVE FOR QUASI ISOTROPIC T300/S-Glass/ NARMCO 5208 HYBRID COMPOSITES TESTED WET (Tension-Tension) AFTER EXPOSURE TO 98% RH/165°F FOR 300 HOURS

APPENDIX III

INDIVIDUAL FATIGUE RESIDUAL
MECHANICAL PROPERTIES DATA

APPENDIX III

INDIVIDUAL FATIGUE RESIDUAL MECHANICAL PROPERTIES DATA

This appendix presents the schedule and individual test specimen results of the studies related to the determination of the residual mechanical properties of the basic and hybrid composites.

Table IX shows specimen orientation, prior conditioning, stress level, applied load cycles and the residual strength, elastic modulus and Poisson's ratio as determined for each specimen.

TABLE IX SUMMARY OF THE RESIDUAL MECHANICAL PROPERTIES OF VARIOUS HYBRID COMPOSITES AFTER TENSION STRESS CYCLING

Specimen Number	Materials and Orientation	Preconditioning	Stress Level (ksi)	Cycles Applied (Cycles)	Residual Strength (ksi)	Residual Elastic Modulus (msi)	Residual Poisson's Ratio (in/in)
1:1-31	$[OL/OR/OL/O_2R/OL/OR/OL]_2$	dry	110	1,000*	-	-	-
32			110	50,000	138.3	14.1	0.27
33			110	100,000	152.1	14.8	0.27
34			110	500,000	173.0	14.4	0.26
35			110	2,000*	-	-	-
1:1-46		wet	110	10,000	166.2	14.1	0.29
47			110	50,000	154.4	13.1	0.28
48			110	100,000	156.4	13.2	0.30
49			110	1*	-	-	-
50			110	800,000	125.5	13.1	0.22
2:1-12	$[OL/O_4R/OL]$	dry	110	10,000	199.6	17.6	0.27
11			110	50,000	196.3	18.2	0.26
13			110	100,000	194.8	18.4	0.27
14			115	37,000*	-	-	-
15			110	1,000,000	176.7	17.7	0.27

*Failed During Cyclic Loading

TABLE IX SUMMARY OF THE RESIDUAL MECHANICAL PROPERTIES OF VARIOUS HYBRID COMPOSITES AFTER TENSION STRESS CYCLING

Specimen Number	Materials and Orientation	Preconditioning	Stress Level (ksi)	Cycles Applied (Cycles)	Residual Strength (ksi)	Residual Elastic Modulus (msi)	Residual Poisson's Ratio (in/in)
2:1 - 21	[$OL/O_4R/OL$]	Wet	135	10,000	187.3	18.8	0.22
2:1 - 22			135	50,000	211.6	18.7	0.25
2:1 - 23			135	100,000	184.0	18.0	0.26
2:1 - 24			135	6,000*	-----	----	----
2:1 - 25			135	1,000,000	204.1	18.5	0.25
1:2 - 11	[$O_2L/O_2R/O_2L$]	Wet	114	10,000	156.8	12.6	0.25
1:2 - 12			114	50,000	161.9	12.7	0.22
1:2 - 13			114	100,000	166.7	12.8	0.28
1:2 - 14			114	500,000	154.2	12.9	0.27
1:2 - 15			114	871,000*	-----	----	----

* Failure During Cyclic Loading

TABLE IX SUMMARY OF THE RESIDUAL MECHANICAL PROPERTIES OF VARIOUS HYBRID COMPOSITES AFTER TENSION STRESS CYCLING

Specimen Number	Materials and Orientation	Preconditioning	Stress Level (ksi)	Cycles Applied (Cycles)	Residual Strength (ksi)	Residual Elastic Modulus (msi)	Residual Poisson's Ratio (in/in)
1:1 - 16	[$\pm$45L/0R/90_2R/0R/$\mp$45L]	Wet	52	10,000	69.6	7.0	0.095
17			52	50,000	78.2	7.6	0.130
18			52	100,000	71.6	6.9	0.144
19			52	500,000	58.6	6.6	0.216
20			52	1,000,000	69.0	6.6	0.334
2:1 - 16	[$\pm$45L/0R/90_2R/0_2R/90_2R/0R/$\mp$45L]	Wet	65	10,000	87.9	7.9	.024
17			65	50,000	85.9	8.3	----
18			65	100,000	82.7	8.6	.094
19			65	325,000*	----	----	----
20			65	500,000	80.2	7.6	.086
1:2 - 16	[$\pm$45L/0R/90R/90L/0_2L/90L/90R/0R/$\mp$45L]	Wet	42	10,000	64.6	6.3	.122
17			42	50,000	71.4	6.4	.121
18			42	100,000	66.0	6.2	.145
19			42	500,000	66.1	6.3	.129
20			42	1,000,000	55.1	---	

* Failure During Cyclic Loading

APPENDIX IV

INDIVIDUAL PROLONGED LOADING TEST RESULTS

Appendix IV INDIVIDUAL PROLONGED LOADING TEST RESULTS

This appendix presents the data for the hybrid composites subjected to prolonged loading. It is restricted to basic specimen data. Individual creep strain versus time curves were presented earlier in Chapter V.

Table X shows the individual specimen by specimen stress levels, fiber orientation, times of load application and residual strength for several samples which ran out.

TABLE X: TENSILE PROLONGED LOADING TEST RESULTS FOR VARIOUS HYBRID COMPOSITES (T-300 GRAPHITE/1014 S-GLASS/NARMCO 5208 EPOXY) TESTED AT ROOM TEMPERATURE.

Specimen No.	Material And Orientation	Test Temperature (°F)	Stress Level		Time To Failure (hours)	Residual Strength (ksi)	Comments
			(% σult)	(ksi)			
11	[OL/OR/OL/OR/OR/OL/ OR/OL]	70	75%	139	602*	173	
13			80%	149	600*	---	
14			82%	152	506*	---	
31	[OL/OR/OR/OR/OR/OL]	70	80%	137	622*	---	
32			70%	120	623*	---	
33			90%	153	622*	---	
34			100%	171	576*	---	
35			120%	205	618*	---	

* Runout, No Failure

TABLE X: TENSILE PROLONGED LOADING TEST RESULTS FOR VARIOUS HYBRID COMPOSITES (T-300 GRAPHITE/1014 S-GLASS/NARMCO 5208 EPOXY) TESTED AT ROOM TEMPERATURE.

Specimen No.	Material And Orientation	Test Temperature (°F)	Stress Level (% σult)	Stress Level (ksi)	Time To Failure (hours)	Residual Strength (ksi)	Comments
21	[OL/OL/OR/OR/OL/OL]	70	75%	118	504*	-----	
22			80%	125	503*	-----	
23			85%	133	193.8	-----	
24			90%	141	433.4	-----	
25			---	149	0.03	------	IMMEDIATE FAILURE
26	[±45L/OR/90R/90R/OR/∓45L]	70	85%	64	1.2	-----	
27			90%	70	0.3	-----	
28			83%	64	173	-----	
29			---	54	594*	-----	
30			80%	62	594*	-----	

* Runout, No Failure

TABLE X: TENSILE PROLONGED LOADING TEST RESULTS FOR VARIOUS HYBRID COMPOSITES (T-300 GRAPHITE/1014 S-GLASS/NARMCO 5208 EPOXY) TESTED AT ROOM TEMPERATURE.

Specimen No.	Material And Orientation	Test Temperature (°F)	Stress Level (% σult)	Stress Level (ksi)	Time To Failure (hours)	Residual Strength (ksi)	Comments
26	[±45L/OR/90R/90R/OR/OR/90R/90R/OR/∓45L]	70	75%	66	508*	--	
27			83%	73	596*	--	
28			80%	70	598*	--	
29				75	0.03	--	Nearly Immediate
30			85%	73	504*	--	
21	[∓45L/OR/90R/90L/OL/OL/90L/90R/OR/∓45L]	70	90%	47	509*	--	
22			85%	52	506*	--	
23			75%	89	605*	--	
24			95%	58	71.5	--	
25			93%	57	2.8	--	

* Runout, No Failure

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